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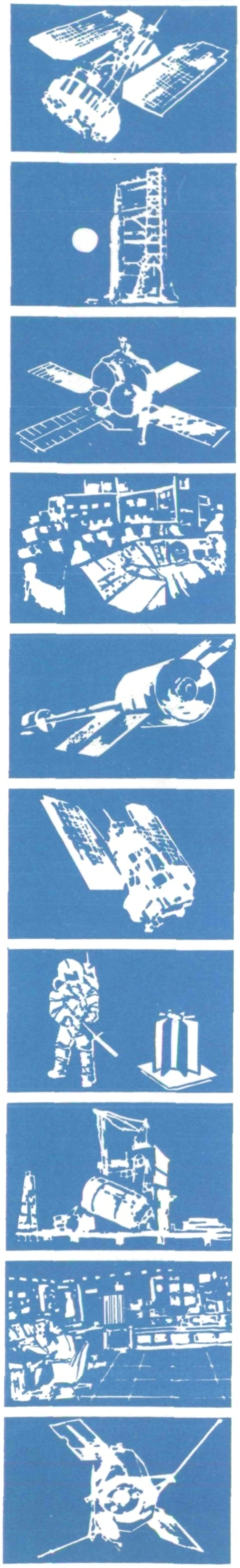

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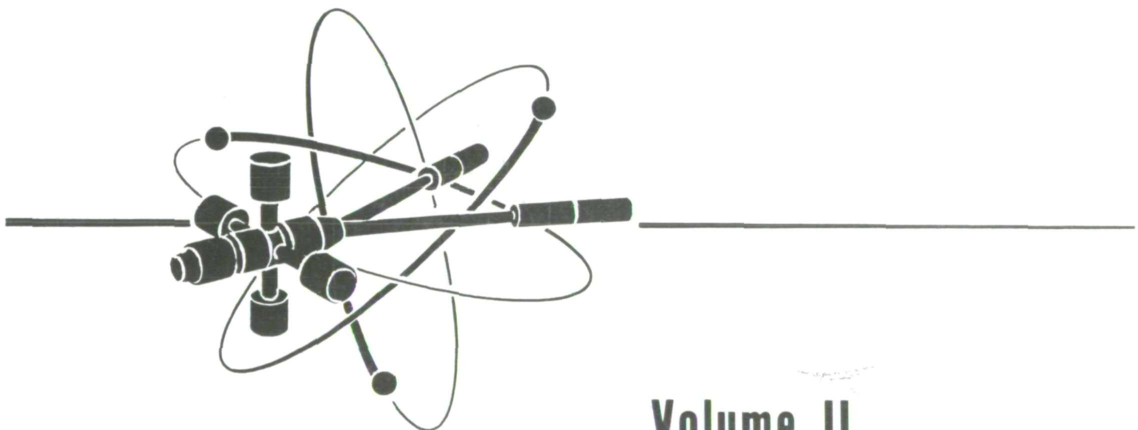

Volume II

SPACE BASE PRELIMINARY NUCLEAR SAFETY ANALYSIS

Part 1

NUCLEAR SAFETY ANALYSIS

GENERAL ELECTRIC

DOCUMENT NO. 72SD4201-2-1
JANUARY 1972

FINAL REPORT

MANNED SPACE FLIGHT NUCLEAR SYSTEM SAFETY

VOLUME II - SPACE BASE PRELIMINARY NUCLEAR SAFETY ANALYSIS

PART 1 — NUCLEAR SAFETY ANALYSIS

PERFORMED UNDER

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FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
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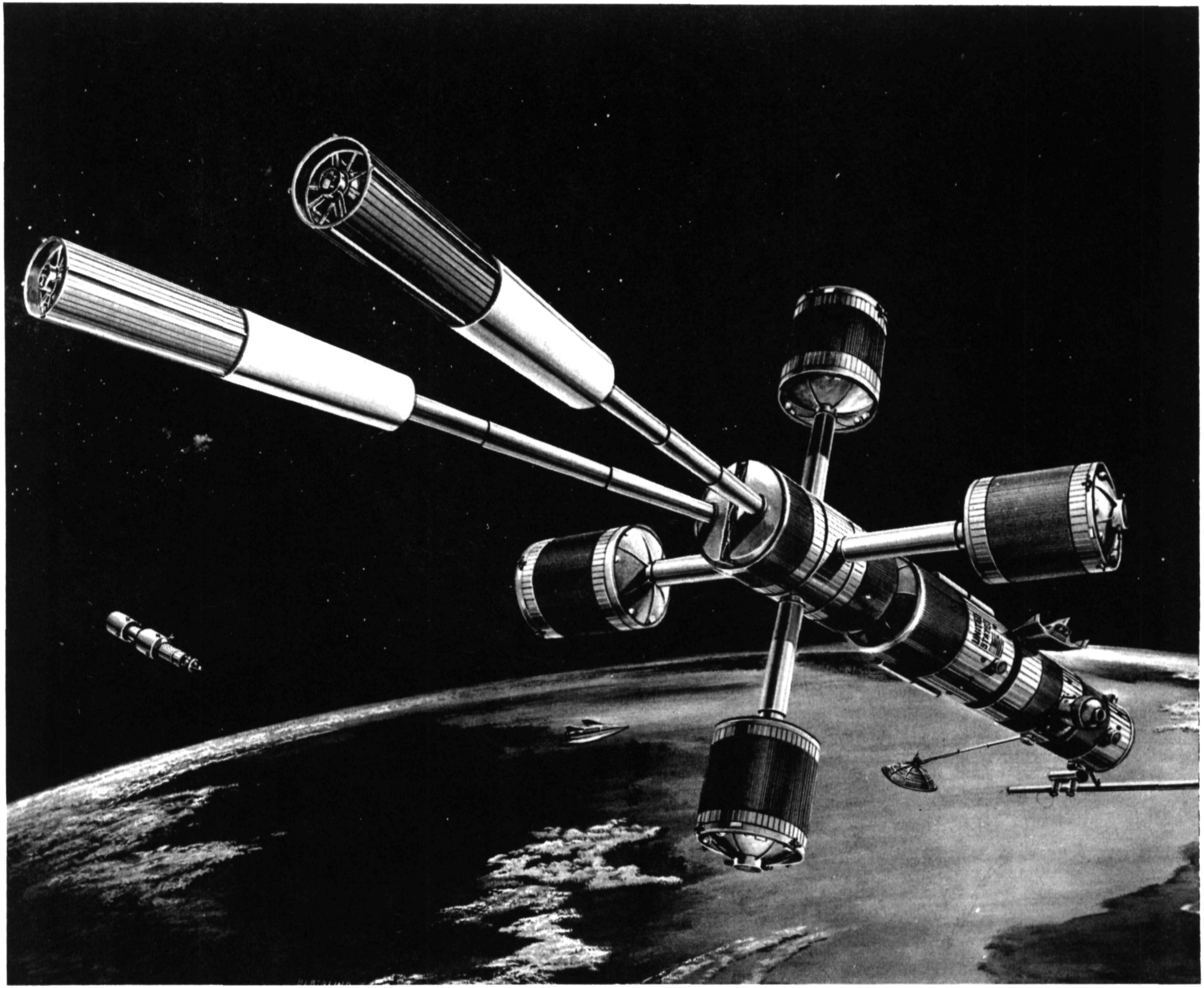
ABSTRACT

This document addresses the nuclear safety aspects of future long duration manned space missions in low earth orbit. Such missions must safely accommodate radiation from the natural space environment and from on-board or interfacing vehicle nuclear sources such as power reactors and isotope heat sources. Nuclear hazards of a typical low earth orbit Space Base mission have been identified and evaluated. Some of the principal nuclear safety design and procedural considerations involved in the launch and orbital operations of such missions are presented. Areas of investigation include radiation interactions with the crew, subsystems, facilities, experiments, film, interfacing vehicles and the nuclear hardware. Results of the analysis indicate (1) the natural space environment can be the dominant radiation source in a low earth orbit where reactors are effectively shielded, (2) with implementation of safety guidelines the reactor can present a low risk to the crew, support personnel, flight hardware and the mission, (3) ten year missions are feasible without exceeding integrated radiation limits assigned to flight hardware, and (4) crew stay-times up to one year are feasible without storm shelter provisions.

The nuclear safety guidelines resulting from the study should be considered in subsequent phases of NASA's manned space program to increase mission effectiveness and overall system safety.



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FOREWORD

The establishment and operation of large manned space facilities in earth orbit would constitute a significant step forward in space. Such long duration programs with orbital stay times of up to ten years would benefit the earth's populace and the scientific community by providing:

1. A flexible tool for scientific research.
2. A permanent base for earth oriented applications.
3. A foundation for the future exploration of our universe.

Specifically, the NASA objectives include earth surveys and scientific disciplines of astronomy, bioscience, chemistry, physics and biomedicine, as well as the development of technology for space and earth applications.

Operational and design requirements, of large manned space vehicles, differ from those of the Mercury, Gemini, and Apollo programs. Of particular interest are the radiation survivability and nuclear safety requirements imposed by nuclear power reactors and isotopes and the long term interaction with the natural radiation environment.

The General Electric Company under contract to NASA-MSFC (NAS8-26283) has performed a study entitled "Space Base Nuclear System Safety" for the express purposes of addressing the nuclear considerations involved in manned earth orbital missions. The study addresses both operational and general earth populace and ecological nuclear safety aspects. The primary objective is to identify and evaluate the potential and inherent radiological hazards associated with such missions and recommend approaches for hazard elimination or reduction of risk.

Work performed utilized the Phase A Space Base designs developed for NASA by North American Rockwell and McDonnell Douglas as baseline documentation.

The study was sponsored jointly by NASA's Office of Manned Space Flight, Office of Advanced Research and Technology, and Aerospace Safety Research and Data Institute. It was performed for NASA's George C. Marshall Space Flight Center under the direction of Mr. Walter H. Stafford of the Advanced Systems Analysis Office. He was assisted by a joint NASA and AEC advisory group, chaired by Mr. Herbert Schaefer of NASA's Office of Manned Space Flight.

The results of the study are presented in seven volumes, the titles of which are listed in Table A. A cross-reference matrix of the subjects covered in the various volumes is presented in Table B.

Table A. Manned Space Flight Nuclear System Safety Documentation

Volume		Document No.
I	Executive Summary	
Part 1	Space Base Nuclear Safety	72SD4201-1-1
Part 2	Space Shuttle Nuclear Safety	72SD4201-1-2
II	Space Base Preliminary Nuclear Safety Analysis	
Part 1	Nuclear Safety Analysis	72SD4201-2-1
Part 1A	Appendix-Alternate Reactor Data (CRD)	72SD4201-2-1A*
III	Reactor System Preliminary Nuclear Safety Analysis	
Part 1	Reference Design Document (RDD)	72SD4201-3-1
Part 2	Accident Model Document (AMD)	72SD4201-3-2
Part 2A	Accident Model Document - Appendix	72SD4201-3-2A
Part 3	Nuclear Safety Analysis Document (NSAD)	72SD4201-3-3
IV	Space Shuttle Nuclear System Transportation	
Part 1	Space Shuttle Nuclear Safety	72SD4201-4-1
Part 2	Terrestrial Nuclear Safety Analysis (C)	72SD4201-4-2*
V	Nuclear System Safety Guidelines	
Part 1	Space Base Nuclear Safety	72SD4201-5-1
Part 2	Space Shuttle/Nuclear Payloads Safety	72SD4201-5-2
VI	Space Base Nuclear System Safety Plan	72SD4201-6
VII	Literature Review	
Part 1	Literature Search and Evaluation	72SD4201-7-1
Part 2	ASRDI Forms	72SD4201-7-2*

*Limited distribution

This study employs the International system of units and where appropriate the equivalent English units are specified in brackets. A list of Conversion Factors and a Glossary of Terms is included in the back of each volume.

Table B. Study Area Cross Reference

* □ 4 PRIMARY DISCUSSION

○ SUMMARY OR SUPPLEMENTAL DISCUSSION

*Section number is included where appropriate

STUDY AREAS	DOCUMENTATION														
	VOL I		VOL II		VOL III				VOL IV		VOL V		VOL VI	VOL VII	
	72SD4201-1 Part 1 Space Base - Executive Summary	Part 2 Space Shuttle - Executive Summary	72SD4201-2 Part 1 PSAR-Space Base	Part 2 Appendix (CRD)	72SD4201-3 Part 1 RDD-Reactor System, Space Base	Part 2 AMD-Reactor System	Part 2A AMD Appendix	Part 3 NSAD-Reactor System	72SD4201-4 Part 1 Space Shuttle Nuclear Safety	Part 2 Terrestrial Nuclear Safety Analysis	72SD4201-5 Part 1 Guidelines - Space Base	Part 2 Guidelines - Space Shuttle	72SD4201-6 System Safety Plan	72SD4201-7 Part 1 Literature Search and Evaluation	Part 2 ASRDI Forms
SPACE BASE PROGRAM															
Reference Vehicle Data	○		□ 3												
Radiation Limits	○		□ 4,A					○	○						
Radiation Environment/Hazards	○		□ 6			□ 3-5							○ 5		
Radiation Effects	○		□ 6,A												
Mission Support Nuclear Safety	○		□ 5										○ 6		
Orbital Operations Nuclear Safety	○		□ 6,7						○ 3-5						
Design & Operational Considerations	○		□ 5,7					○	○ 3-5						
Guidelines & Requirements	○		○					○			□	○	○ 5		
Reactor System Studies	○		□ 7	□											
Terrestrial Safety Analysis	○														
Reference Design					□				○ ABC						
Accident Models & Source Terms						□	□			○ 2,3					
Risk Analysis								□		○ 2,3					
System Safety Plans													□		
Technology Development Required	○		□ 8					○					○ 7,8		
SPACE SHUTTLE PROGRAM															
Reference Vehicle Data		○							□ ABC						
Nuclear Payload Integration		○							□ 3-5						
Design & Operational Considerations		○	○						□ 3-6						
Guidelines and Requirements		○	○						○ 3-6		○	□			
Terrestrial Safety Analysis		○			○	○		○	○ 6	□					
LITERATURE REVIEW DATA															
Approach and Cross Index														□	
ASRDI Forms															□

ABBREVIATIONS

ADM	Add-on Disposal Modules
AEC	Atomic Energy Commission
ALS	Advanced Logistic System (Space Shuttle)
AMD	Accident Model Document
ASRDI	Aerospace Safety Research Data Institute
BOL	Beginning of Life
BPCL	Brayton Power Conversion Loop
BRU	Brayton Rotating Unit
DOD	Department of Defense
DOT	Department of Transportation
ECLS	Environmental Control and Life Support
EM	Electro Magnetic
EOD	Earth Orbital Decay
EOL	End of Life
EOM	End-of-Mission
EPS	Electrical Power System
ETR	Eastern Test Range
EVA	Extra Vehicular Activity
FC	Fuel Capsule
FPE	Functional Program Element
G&C	Guidance and Control
GSE	Ground Support Equipment
HX	Heat Exchanger
ICRP	International Committee on Radiation Protection
IDM	Integral Disposal Module
INT-21	Intermediate Saturn Stages
IR	Infrared
IRV	Isotope Re-Entry Vehicle
IU	Instrument Unit
IVA	Intra Vehicular Activity
KSC	Kennedy Space Center
LCC	Launch Control Center
LD	Lethal Dose (% Probability)
LOX	Liquid Oxygen
LV	Launch Vehicle
MCC	Mission Control Center
MDAC	McDonnell Douglas Corporation
MHW	Multi-Hundred Watt
ML	Mobile Launcher
MPC	Maximum Permissible Concentration
MSC	Manned Spacecraft Center
MSFC	Marshall Space Flight Center
MSS	Mobile Service Structure
NA	Non-Applicable
NAB	Nuclear Assembly Building
NAR	North American Rockwell
NASA	National Aeronautics and Space Administration
NC	Non-Credible
NCRP	National Committee on Radiation Protection
NSAD	Nuclear Safety Analysis Document
OPSD	Orbital Propellant Storage Depot
ORNL	Oak Ridge National Laboratory
PCS	Power Conversion System
PM	Power Module
PSAR	Preliminary Safety Analysis Report
RAD	Radiation Absorbed Dose
RCS	Reaction Control System
RDD	Reference Design Document
REM	Roentgen Equivalent Man
RMU	Remote Maneuvering Unit
RNS	Reusable Nuclear Shuttle
R/S	Reactor/Shield
RSO	Radiation Safety Officer
RTG	Radioisotope Thermoelectric Generator
SB	Space Base
SAR	Safety Analysis Report
SEHX	Separable Heat Exchanger
S-IC	First Stage of Saturn V
S-II	Second Stage of Saturn V
SNAP	Space Nuclear Auxiliary Power
SNAPTRAN	Space Nuclear Auxiliary Power Transient
TAC	Turbine Alternator Compressor
TEM	Thermoelectric Electro Magnetic Pump
TLD	Thermo Luminescent Dosimeter
USAF	United States Air Force
VAB	Vehicle Assembly Building

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SECTION 1

INTRODUCTION

KEY CONTRIBUTORS

E. E. GERRELS

SECTION 1
INTRODUCTION

1.1 GENERAL

This study addresses the radiological safety aspects of manned space missions employing nuclear reactors for prime electrical power and involving extended stay times in low earth orbit. A Manned Space Base employing pertinent safety related features from both the McDonnell Douglas and North American Rockwell Phase A studies (Reference 1-1, 1-2) was utilized for reference mission purposes. Results of the study are considered applicable for future design and development phases of manned space programs.

1.2 OBJECTIVES

The primary objective of this preliminary nuclear safety analysis is to identify potential and inherent radiological hazards of a representative Space Base program and to recommend approaches for hazard elimination or reduction to acceptable risk levels. The specific study objectives are listed in Table 1-1.

Table 1-1. Specific Study Objectives

1.	Perform a comprehensive, qualitative nuclear safety evaluation of a Space Base program
2.	Perform gross hazard and failure mode and effects analyses, and establish failure probabilities for those nuclear related situations that could lead to risk to the general populace, the ecological system, the crew, and any Space Base program equipment including experimental equipment.
3.	Determine the impact of the radiological hazards on a Space Base program and the Earth's populace and ecology
4.	Determine the influence of a Space Base program safety requirements on the design and operation of nuclear hardware.
5.	Evaluate the impact of the nuclear safety criteria, guidelines, and requirements developed during the study on the nuclear power system and the Space Base mission.
6.	Investigate the effects of radiation on operational and experimental equipment associated with the Space Base program.
7.	Develop design and operational criteria, procedures, guidelines, and requirements governing radiological system safety for a Space Base program.
8.	Prepare Preliminary Safety Analysis Reports covering the reactor power system and Space Base in two separate volumes.
9.	Prepare applicable portions of a System Safety Plan (SSP) covering nuclear safety for a Space Base program.
10.	Prepare inputs to NASA's ASRDI data bank for all pertinent reference material used in the study and the final study documents.

A Space Base program encompasses a diversity of support equipments and a broad experiment program. Therefore, it is expected that results from this safety evaluation will be applicable not only to a Space Base, but to the general class of advanced, manned, earth-orbital space missions. Performing this type of evaluation at the early stages of a program, permits design and procedural safety features to be evolved concurrently with the evolution of an overall program resulting in effective and timely implementation for maximum safety.

1.3 SCOPE

This document, Volume II, addresses the identification and evaluation of radiological hazards associated with a Space Base mission. The potential effects of these hazards on mission operations, support activities, crew, subsystems, experiments and interfacing vehicles are presented. Design, operation and procedural considerations which reduce or eliminate these radiological hazards are identified. The evaluation of the effects Space Base nuclear reactors have on terrestrial nuclear safety is contained in a separate document, Volume III entitled "Preliminary Safety Analysis Report-Reactor System."

Safety related guidelines and requirements resulting from the overall study are identified in the main body of the reports and are formally identified and described in Volume V. The nuclear safety requirements of a System Safety Plan for a Space Base Program are contained in Volume VI.

The basic ground rules employed in the study are summarized in Table 1-2.

Table 1-2. Study Ground Rules

- The baseline mission definitions studied in this program are the Space Base mission designs by McDonnell-Douglas and North American Rockwell as prepared for MSFC and MSC, respectively.
- The experiment program analyzed is that outlined in the OMSF publication, "Candidate Experiment Program for Manned Space Stations" and its subsequent iterations.
- The baseline Space Base power system consists of a zirconium-hydride reactor(s) coupled with a Brayton cycle conversion system.
- The study considers the total Space Base system nuclear safety concept including crew/personnel safety, mission success, safety of the ecological system and of the general populace.
- Means for effecting all normal and in-flight maintenance and repair of nuclear systems necessary for crew survival and mission continuation were part of this study.
- Reliability and maintainability aspects of critical (nuclear) systems, like the reactor power system, received special emphasis.

1.4 ORGANIZATION

In order to facilitate the location of results and supporting information, the intent and interrelation of the various sections of this volume are presented below:

- Section 2 Summary - A brief summary of key conclusions regarding nuclear safety derived from the analyses of manned space flight nuclear system safety.

- Section 3 Reference Space Base Program - A definition of the mission, and significant systems and design features of a Space Base program including key assumptions and models used in the analyses.

- Section 4 Nuclear Radiation Exposure Limits Summary - A summary of the nuclear radiation exposure limits for personnel, subsystems and experiments which were used in the radiological hazard evaluations.

- Section 5 Mission Support Operations Radiological Hazard Analysis - The analysis of the impact of radiological hazards on Space Base Program mission support equipment and personnel is contained in this section. It is organized by mission phase (Prelaunch, Launch/Ascent, Orbital, End of Mission). Topics covered include packaging, transporting, handling, checkout, launch pad activities, facility requirements, recovery/disposal operations, etc. Design, operational and procedural considerations which would minimize radiological hazards associated with the mission support functions, are identified.

- Section 6 Space Base Operations Radiological Hazard Analysis - This section addresses the effect of radiological hazards on the flight crew and hardware elements of a Space Base Program including subsystems, the experiment program and interfacing vehicles. The potential hazards associated with the various mission phases are defined and the rationale used in identifying these hazards is discussed. The hazards are analyzed to determine their effect on Space Base Program elements. Design, operational and procedural considerations which are presently incorporated or should be incorporated to minimize the radiological hazards are presented. The emphasis in this section is on the flight hardware associated with a Space Base Program, as opposed to the Mission Support Requirements which are discussed in Section 5.0.

- Section 7 Special Studies - This section contains the results of several design and operations studies of the reactor power module and radiological control programs.

- Section 8 Research and Technology Requirements - This section identifies areas which require further investigation or techniques which require development.

- Appendixes - Appendix A contains the detailed results of the radiation limit investigation. Appendixes B, C, D and E contain other supporting data. Appendix F is contained under separate cover (Volume II, Part 1A) due to classification.

1.5 REFERENCES

1-1. "Space Base Concept Data;" MDC G0576 prepared under contract NAS 8-25140; McDonnell Douglas Corporation; June 1970.

1-2. "Space Base Definition;" SD 70-160 prepared under contract NAS 9-9953; North American Rockwell; July 1970.

SECTION 2

SUMMARY

KEY CONTRIBUTORS

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E. E. GERRELS

SECTION 2
SUMMARY

2.1 GENERAL

Safety analyses oriented to radiological safety of a program such as a Space Base were applied in the Space Base Nuclear System Safety Study. The overall study, development of data and principal conclusions are intended as a point of departure for subsequent phases of manned space flight programs where similar radiological hazards will be encountered.

2.2 REFERENCE MISSION

A reference mission was established to allow identification and analysis of potential hazards and to provide a reference design against which the guidelines and recommendations resulting from the study could be established and evaluated. The reference mission incorporated significant aspects related to nuclear safety from the Phase A Space Base studies of North American Rockwell and McDonnell Douglas (Reference 2-1, 2-2). Several of the mission features are listed in Table 2-1. Basic elements of the hybrid vehicle are common modules 10 m (33 ft) in diameter comprising artificial and zero gravity habitation and work areas. Several subsatellites in near proximity orbits are serviced by the Base. When "built-up", the nominal Base can accommodate 50-man crews in low earth orbit for a 10-year mission. Such a facility requires large amounts of electrical power. Nuclear reactors are the prime candidates.

The study reference design employs two Zirconium Hydride (ZrH) thermal reactors, coupled with redundant Brayton cycle conversion systems, to provide a total power output of 100 kWe. Capability of a single reactor to provide the entire load for short periods is assumed. Nominal lifetime of the reactor is assumed to be five years with lifetimes of the power conversion systems somewhat shorter. Repair and/or replacement of the reactor and power conversion systems is therefore a necessity during a 10 year mission. A reactor power module disposal system is provided to obtain separation of the "spent" or damaged power module from the Base and a subsequent boost into a high earth orbit.

Table 2-1. Space Base Mission Features

Reactor System	2-ZrH reactor-Brayton power modules, each with 330 kWt (50 kWe) nominal rating-600 kWt maximum
Configuration	Power modules on extendable booms of zero-g core. Artificial-g rotating hubs.
Orbit	500 km (273 nm), 55° inclination
Launch Vehicle	Saturn INT-21 (launch of 1 or 2 power modules)
Launch Trajectory	46° launch azimuth from KSC; Eurasian over-fly
Lifetimes	Mission - 10 years, reactor - nominally 5 years, power conversion system - nominally 2.5 years
Crew Size	50 (nominal) with 90 to 180 day crew rotation cycle
Experiments	Extensive on-board and orbiting subsatellite program
Logistics	Space Shuttle - primary logistics vehicle, Space Tug - final rendezvous and docking of power module
Power Module Disposal	Boost by integral Disposal System to 990 km high altitude disposal orbit.
Reactor Shield	Shaped 4π lithium hydride neutron shield, tungsten gamma shield } 1 mrem/hr at nearest habitable interface
Space Base Definition	North American Rockwell and McDonnell Douglas Phase A studies.

The mission was divided into four phases: (1) Prelaunch, (2) Launch/Ascent, (3) Orbital Operations, and (4) End of Mission. Launches of prime hardware utilize Saturn INT-21's and Space Shuttles. The ten-year operational phase incorporates an extensive experimental program with resupply and logistic support by Space Shuttles. The End of Mission Phase is characterized by the safe disposal and/or recovery of the nuclear hardware.

2.3 MISSION NUCLEAR HAZARDS

The nuclear hazards associated with the mission were identified as either inherent to the mission or caused by "accident" situations. The reactors constitute an inherent "normal" hazard during most phases of the mission. The reactor was assumed to undergo low power

criticality checks prior to arrival at the launch center and consequently the fission product inventory prior to reactor orbital start-up was held to a minimum. Several nuclear sources, in addition to the power reactors, may be a part of, or interface with a Space Base. Solar flare events, galactic cosmic and earth trapped radiation are significant radiation contributors in low earth orbits. Interfacing vehicles such as a Reusable Nuclear Shuttle were also considered along with isotopic sources located within the Base modules. The expected radiation environments of on-board nuclear sources and the natural environment were classified as "normal", whereas for example, a reactor excursion or inadvertent operation of an X-ray machine was termed an "accident" situation. A summary of the potentially hazardous situations considered for each mission phase is shown in Table 2-2. In addition to the nuclear hazards, attention was also directed to the handling of the liquid metal inventory and the potential thermal hazards the nuclear sources exhibit.

Table 2-2. Hazard Identification

	HAZARD SOURCES		MISSION PHASES					
			PRELAUNCH	LAUNCH AND ASCENT	OPERATION			EOM
					BUILD-UP/	REPLACE	OPER.	
SPACE BASE	REACTOR POWER MODULES	REACTOR	A	A	N, A	N, A	N, A	N, A
		PRIMARY LOOP	A		N, A	N, A	N, A	N, A
		ACTIVATED COMPONENTS	A	A	N, A	N, A	N, A	N, A
	MATERIAL PROCESSING LAB	X-RAY MACHINE			N, A		N, A	
	BIOSCIENCE LAB	RADIOACTIVE TRACERS			N, A	N, A	N, A	N, A
INTERFACES	NATURAL ENVIRONMENT	EARTH TRAPPED RADIATION			N	N	N	
		GALACTIC COSMIC RADIATION			N	N	N	
		SOLAR RADIATION			N	N	N	
	NUCLEAR SHUTTLE	REACTOR					N, A	
	NUCLEAR PROP DEPOT	REACTOR					N, A	
			N – NORMAL		A – ACCIDENT			

POTENTIAL ADDITIONS

ISOTOPE BRAYTON POWER SYSTEM	N, A	A	N, A	N, A	N, A	N, A
ISOTOPE HEAT SOURCES	N, A	A	N, A	N, A	N, A	N, A

2.4 MISSION RADIATION EXPOSURE LIMITS

In order to evaluate the effects of radiation on a Space Base mission, a reference set of exposure limits for personnel, typical subsystems and experiments were compiled. The detailed listings are contained in Appendix A of this volume. Limits assigned to personnel were based on currently accepted or proposed agency guidelines prescribed for crewmen, ground support personnel, and the general populace. Maximum radiation limits for the crewmen under closely controlled conditions were set higher than those for ground radiation workers (e.g., yearly dose to skin (0.1 mm depth) for a crewman is 225 rem whereas 30 rem is specified as the maximum for ground radiation workers).

The sensitivity of subsystem electronic components and other materials to radiation was described in terms of bulk damage and ionization effects. Damage levels are primarily total dose dependent. In general, film, emulsions and solid state electronics were shown to have the lowest tolerance levels.

Experiments are comprised of electronics and materials similar to that used in various subsystems. However, in addition to considering the total dose limitations, dose rates affecting experiment data degradation due to "noise" were considered. Bioscience experiments exhibited a wide range of sensitivity to total accumulated dose, dependent on the stage of development of the organism. In most cases, biological experiments are considered more resistant to radiation than man, this being particularly true of the invertebrates.

A wide range of subsystem and experiment sensitivities were obtained, indicative of the importance of specifying the objectives of the subsystems and experiments to be used in the mission prior to establishing radiation limits, which, if not evaluated adequately, could lead to overly stringent and unrealistic requirements.

2.5 NUCLEAR SAFETY IN MISSION SUPPORT OPERATIONS

2.5.1 THE MISSION SUPPORT HAZARD

Nuclear hardware operations during prelaunch, abort and recovery phases of the mission constitute the principal mission support radiological hazards, whereas the environment must also be considered during orbital operations. Isotopes continuously emit radiation and produce thermal energy. Preoperational cooling, anti-criticality containment and special shielding are required to enable ground support personnel area accessibility and maintain support and prime hardware integrity. Nuclear reactors present a considerably different situation. Preoperational checks of a clean non-operating reactor can be planned to provide minimum radiation hazards. What may prove to be a more difficult ground support operation problem is the presence of rather extensive quantitites of liquid metals in the primary and intermediate coolant loops.

2.5.2 MISSION SUPPORT HAZARDS ANALYSES

A summary of key results obtained in an analyses of the hazards during mission support operations is presented below.

OPERATIONS AT THE LAUNCH CENTER

The reactor can be designed to present minimum hazards during prelaunch operations. Fission product inventories will be negligible when minimum power level criticality tests are performed at the point of manufacture and no such tests are performed at the launch center. Radiation levels above 0.15 rem, due to a 100 MW-sec excursion (considered a worst case and improbable condition) can be confined to within 5 km (3 miles) from the launch site and would have relatively no effect on personnel stationed in the vicinity of the Vehicle Assembly Building (VAB) or immediate fall-back areas. As a reference, the normal sea level yearly radiation background is noted to be 0.15 rem.

A universal reactor power module transport and storage trailer provided with environmental protection and status monitoring can serve in transport, storage, checkout and integration operations to minimize handling functions and potentially hazardous situations.

Liquid metal fire protection is incompatible with present fire suppression at the launch center. Modifications in present fire protection techniques are required, including the addition of liquid metal fire suppressants, isolation barriers, sumps, etc. Liquid metal fire hazards can be reduced by minimizing the liquid metal inventory (e.g., by use of non-liquid metal radiators), provision of double wall containment, and the use of inert gas blankets during storage or transport.

The necessity and desirability of integrating and testing the reactor power module within the VAB is questionable. Consideration should be given for a direct transfer of the power module from the Nuclear Assembly Building (NAB) to the Launch Pad. A power module simulator could be used for system integration tests within the VAB.

Isotope heat sources require redundant prelaunch cooling and should be integrated with the launch vehicle and Space Base modules as late in the countdown sequence as feasible.

FACILITIES

Extensive use can be made of existing facilities at the John F. Kennedy Space Center. Special facilities which would be required to support the extensive nuclear hardware of the reference Space Base Program include (1) a controlled area Nuclear Assembly Building (NAB) where reactor and isotope nuclear hardware would be received, stored and checked-out, and (2) a liquid metal servicing facility providing, as a minimum, a capability to render safe a damaged and possibly leaking liquid metal component such that it could be shipped back to the factory for repair.

The special and existing facilities designated to support a nuclear power module must provide nuclear radiation protection and monitoring, environmental protection and liquid metal fire suppression capability.

RANGE SAFETY

The launch of nuclear materials necessitates a new look at range safety procedures, particularly in regard to destruct options and launch trajectories which traverse populated areas such as the Eurasian continent. To minimize potential fragmentation damage to nuclear

hardware and the subsequent release of nuclear material and/or fission products on populated territories, consideration should be given to (1) safing the destruct system over the territory or (2) release of the nuclear hardware moments before destruct initiation. Timing is critical and the effects of destruct delays must be carefully evaluated. Alternatives to these procedures include the incorporation of fragmentation shields or rather extensive launch escape systems.

RADIOLOGICAL CONTROL

Radiological control at KSC and at potential impact points can be most effectively administered by (1) the establishment and rigid control of radiation designated work and exclusion areas and (2) the prompt use of impact/recovery teams and location devices. Quick response recovery and decontamination teams are required at KSC. A mobile team coupled with advance warning of impending impact zones can minimize the potential hazards to the general world populace.

Mission control can provide assistance in the on-board radiological monitoring and control of the crew. Cumulative radiation dose records can be kept. Periodic Shuttle logistic flights can bring to the earth radiation emulsions and urine specimens which would be processed on the ground. Special packaging and radiation shielding arrangements are required in transport to allow for an accurate record of radiation doses received. Based on records received from orbit and ground data systems, crew assignement and rotation schedules would be prepared or adjusted.

2.6 NUCLEAR SAFETY IN ORBITAL OPERATIONS

2.6.1 ORBITAL OPERATIONS RADIATION HAZARDS

The space environment in low earth orbit is the major radiation contributor to the Base, providing a nominal 3 mrem/hr through 1.6 g/cm^2 module shielding. The trapped radiation belts provide a majority of this dose in the reference 500 km (273 nm) 55 degree inclination orbit. In addition, the depth dose from a single high intensity solar flare can result in at least 4 rem. Due to the ability to adequately shield a reactor, its contribution at the nearest

habitable area can be kept quite low. In the reference Space Base, the dual reactor contribution is 1 mrem/hr. The yearly percentage attributed from all sources for a typical Space Base is shown in Table 2-3. As is shown, the use of nuclear reactors on a Base is a minor contributor to the total annual radiation dose.

Table 2-3. Estimated Yearly Dose Percentage Contributions

Source	Percent
Natural Radiation	60
Solar Flares	26
Nuclear Reactors	12
Other Sources	2

2.6.2 ORBITAL OPERATIONS HAZARD ANALYSIS

A summary of key results obtained in an analysis of the hazards during orbital operations is presented below.

GENERAL ORBITAL OPERATIONS

The analysis has shown that ten-year orbital missions with crew stay-times of one year are feasible. Predicted solar flare activity and practical Space Base Module shielding necessitate storm shelter provisions for crew stay-times of over one year.

The natural space radiation environment in typical Space Base earth orbits can present a more severe hazard to the crew and space subsystems than a well shielded operating reactor. Lighter reactor shields and higher operating thermal power levels would increase the radiation levels and likewise increase the hazards to the crew, subsystems and experiments.

In addition to the nuclear power reactors and the natural environment, there are several additional potential sources of radiation (i.e., isotope heat sources, tracers, X-ray emitters, etc). It is important that the isotope heat sources and tracers be adequately shielded and contained to prevent contamination within the Base and reduce doses to the crew and sensitive equipment.

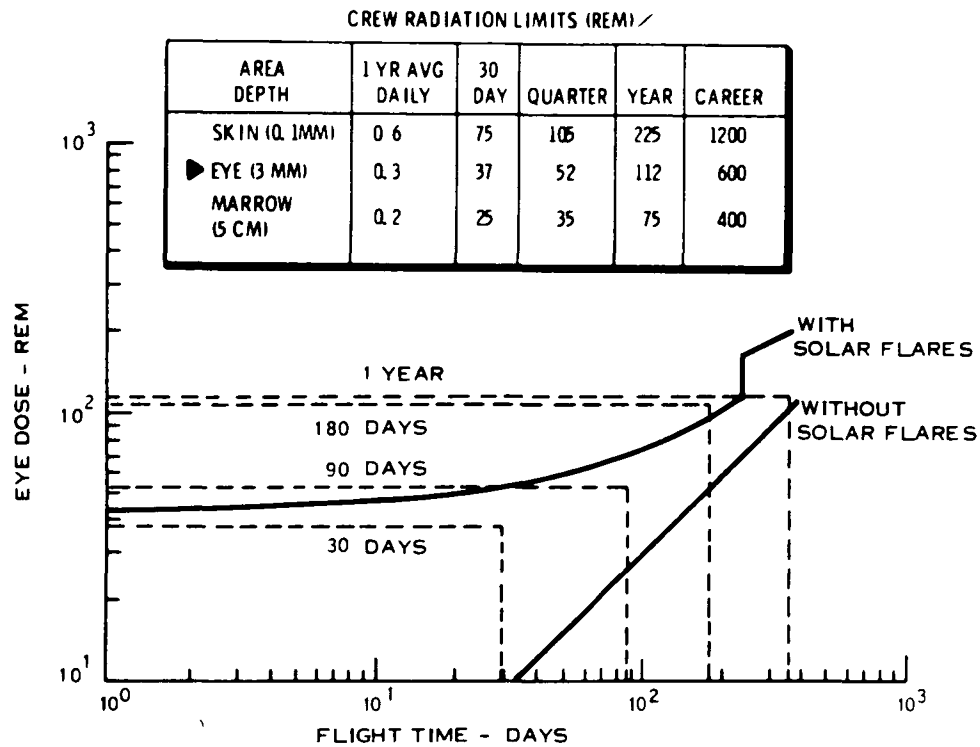
Several potential, however remote, accidents involving the reactor in orbit can present a considerable radiation hazard to the crew. A reactor excursion and/or disassembly in orbit can result in highly radioactive debris around the Base. Emergency plans may require a rapid response orbit change of the Base and/or the ejection of the damaged power module away from the Base followed by a disposal into high earth orbit. A collision or impact of debris with the reactor shield in orbit can result in a shield leak (loss of H_2) and therefore increased radiation with time. A compartmentalized shield and/or increased shield cladding combined with leak detection instrumentation can minimize the hazard and allow time for repair or replacement.

CREW EFFECTS

Although radiation levels of 3 to 4 mrem/hr are relatively low, when one considers the integrated doses for a 6-month crew stay-time and 10-year mission lifetimes, radiation limits on the crew and hardware must be considered. The eye dose limits as defined by the National Academy of Sciences appears to make the eyes the limiting organ. The integrated dose to the eye as a function of flight time has been calculated and shown in Figure 2-1. The doses are shown with and without solar flare events. The solar flare data includes the possibility of an event on the first day and another event occurring 250 days later. Increased shielding in headgear can help to reduce the dose to the eyes, however consideration should be given to the provision of a storm shelter for crew stay-times of over one year or to prevent the necessity of replacing the entire crew should a major solar flare event occur.

SUBSYSTEM EFFECTS

The effects of the radiation environments on the subsystems of the Base exclusive of the reactor power module were determined. The principal radiation considerations are bulk (crystal) damage and ionization (surface) effects associated with semiconductor electronics, ionization effects in materials and dynamic interference effects in sensors. A summary of the equivalent 1 Mev neutron bulk damage effects on typical Space Base subsystems is shown in Figure 2-2. Figure 2-3 shows the ionization effects. The most sensitive components to bulk damage are light emitting diodes in solid state displays and high power semiconductors. Organic materials subjected to oxygen environments, semiconductors - particularly MOS devices, and film - are most sensitive to ionization.



AREA DEPTH	1 YR AVG DAILY	30 DAY	QUARTER	YEAR	CAREER
SKIN (0.1MM)	0.6	75	105	225	1200
EYE (3 MM)	0.3	37	52	112	600
MARROW (5 CM)	0.2	25	35	75	400

Figure 2-1. Crew Exposure

The expected 10-year reactor and natural radiation environment integrated doses have been superimposed on the figure to indicate potential subsystem incompatibilities. It is recognized that film will be periodically resupplied and would not normally be subject to the long term environments. However, where threshold damage to electronics may be indicated, radiation hardening techniques such as piece part selection can be employed to provide hardware relatively insensitive to the total radiation environment expected for a 10-year mission.

EXPERIMENT EFFECTS

Integral or detached modules will contain a multi-disciplined set of experiments capable of taking precise measurements. Radiation particle flux rates above some threshold level could cause "dynamic interference" where noticeable degradation of data quality results (a signal to noise ratio of 10 to 1 is assumed). Interference is frequently present where the environmental radiation spectrum has components (gamma rays, etc.) identical to those sought in the experiment. Permanent experiment damage can also result, but generally dynamic interference would occur prior to severe damage and subsequent failure of experiment hardware.

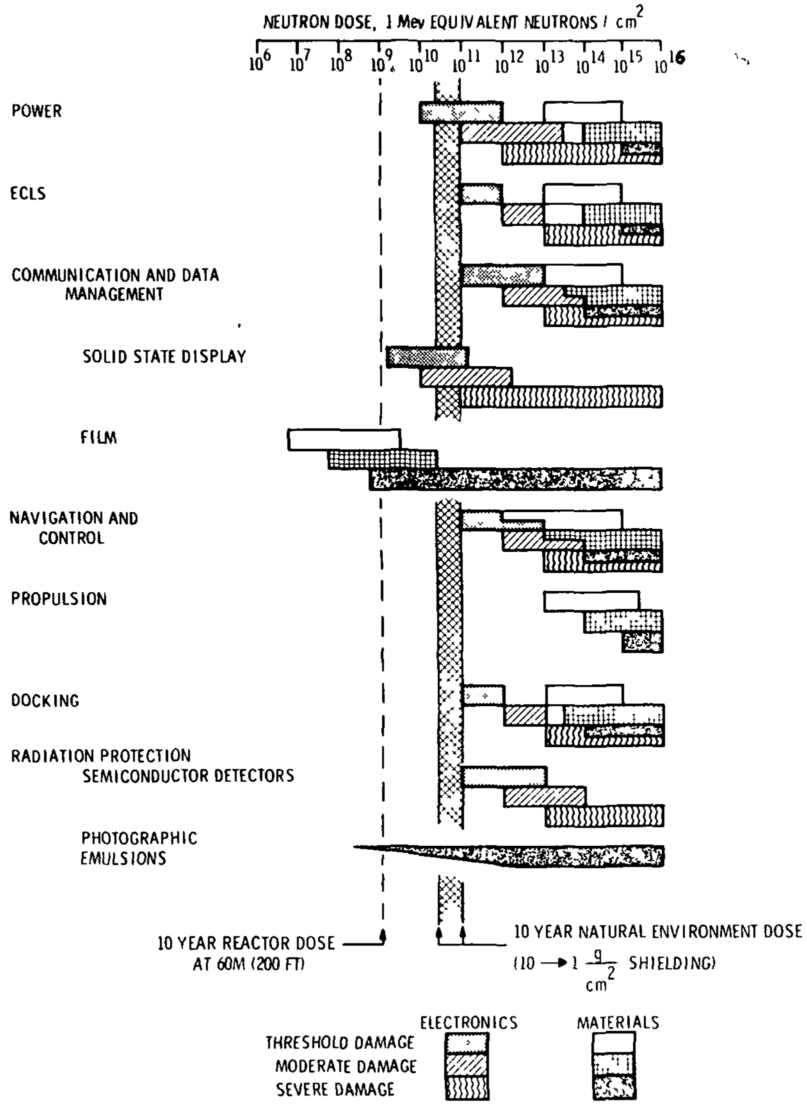


Figure 2-2. Summary of 1 Mev Neutron Effects in the Space Base Support Subsystems

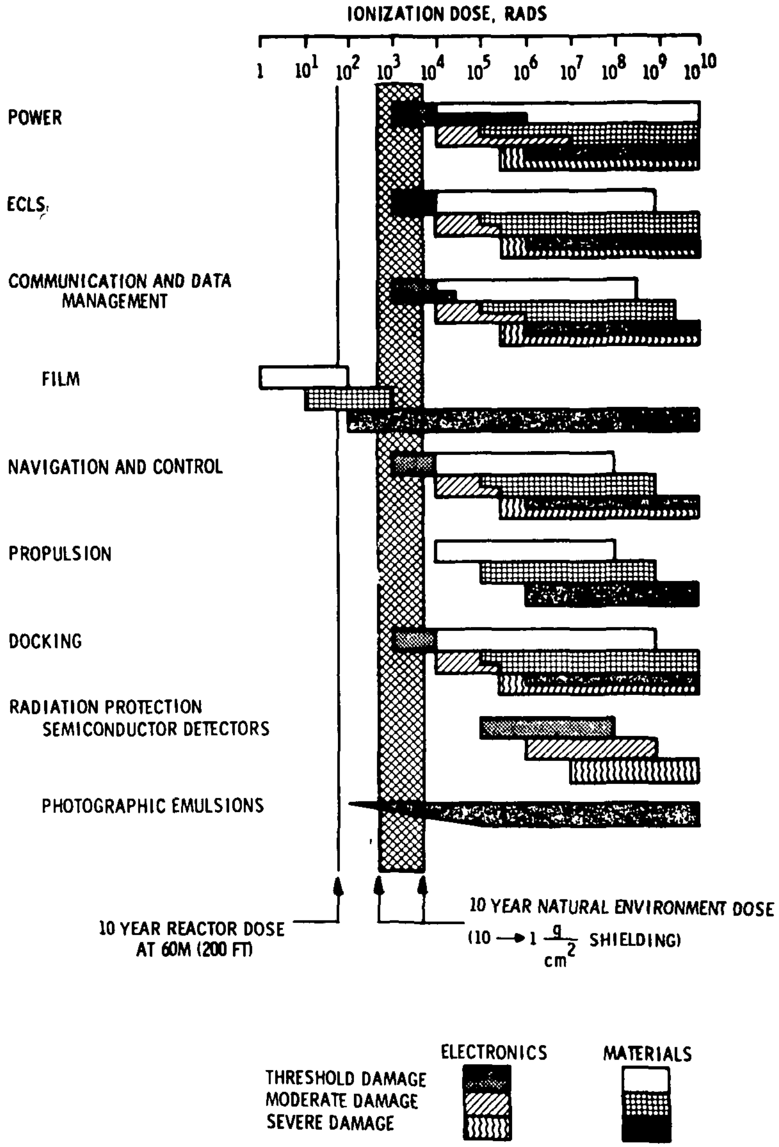


Figure 2-3. Summary of Ionization Effects in the Space Base Support Subsystems

Several of the experiments identified in the "NASA Blue Book" used as reference experiments in the study are susceptible to dynamic interference in certain portions of the orbit, particularly through the South Atlantic anomaly. Especially sensitive are devices such as the airglow photometer (FPE 5.6), the nuclear gamma ray spectrometers for high energy stellar astronomy (FPE 5.5) and grazing incidence X-ray telescopes (FPE 5.1). Where interference is attributed to the natural environment, temporary curtailment of the experiment operation may be advisable. Radiation interference from the reactors may be reduced by shielding or changing the experiment location. The latter approach is recommended for the two astronomy packages (FPE 5.1, 5.5) where detached "free-flying" modules should be considered. Typical minimum approach distances from the reactor for free-flying modules range from over 1 to 100 kilometers to prevent dynamic interference.

Biological specimens used in space experimentation programs have a wide range of radiation sensitivities ranging from a few Rads to thousands of Rads. The radiation protection required is dependent on the specimen type age and experiment objective. Monitoring the radiation dose to sensitive bioscience experiments, such as fertilization and embryolic processes, is recommended.

FILM EFFECTS

Photographic film and special emulsions, apart from special radiation detectors and a limited class of biological specimens, are perhaps the most sensitive material to the radiation environment. Film deterioration during storage and use in space may present one of the most frequent resupply requirements. High speed film (ASA 400-800) stored or contained within 20 g/cm^2 shielding must be used and developed within 25 to 50 days after delivery to a Space Base in order to insure minimal fogging effects. A solar flare could eliminate the entire onboard film supply.

OPERATIONS WITH OTHER RADIOLOGICAL SOURCES

Isotope heat sources and tracers could be contained within the habitable Space Base modules. It is particularly important that sealed sources (capsules) and open sources (isotope tracers) be operated in areas that can be completely isolated to prevent contamination of large areas in the event of a release. Ventilation and waste management systems must be carefully designed.

INTERFACING VEHICLE CONSIDERATIONS

Module buildup, logistic resupply and experiment support activities require frequent interface with various supporting vehicles. The normal Space Base reactor environment allows for Space Shuttle and Tug rendezvous at any view angle if loiter times are minimized and braking gate velocities are maintained within currently planned specifications. A crewman flying a maximum orbit rendezvous mission with the flight path directly head-on to the power module (worst case) was calculated to receive a maximum integrated dose of approximately 24 mrem of which only 4.7 mrem is attributed to the reactor power modules.

Detached free-flying subsatellites and logistic vehicles which employ film must be restricted in their operations and movement in the vicinity of the reactors in order to avoid reducing useful film life or degradation of data. However, at distances of greater than 3 km, the natural environment is usually the limiting radiation source.

The nuclear reactor radiators reject considerable quantities of heat from the Brayton cycle conversion system in the range of 350° to 500°K. This condition poses a potential hazard to EVA activities in the area of the radiators and also may interfere with IR scanners used in rendezvous vehicles.

Reusable Nuclear Shuttle (RNS) fly-by requirements limit doses at the Base to 0.1 rem per pass. Separation distances of over 125 km should be considered during the RNS reactor propulsion operations where maximum dose rate view angles could be attained. Shutdown (loiter) distances during RNS and Base logistic operations allow approaches within a few kilometers without experiencing experiment dynamic interference of the Base experiments.

MAINTENANCE AND REPAIR

Maintenance and repair operations within the Base are generally not directly affected by the nuclear environment unless operations are in near proximity to nuclear sources. EVA operations, however, are outside the module shielding which increases the dose to the skin by a factor of two, the corresponding increase to the depth dose being substantially less.

The dose to the rear of the reactor power modules is highly dependent on shield configuration and reactor power level. In the reference configuration, the dose only becomes a significant factor when near the reactor, the dose at 8 m from the reactor being less than 43 mrem/hr with both reactors operating. The power modules themselves can provide a reasonable maintenance capability of the power conversion system and associated components within a protected and possibly pressurized "engine room" located in the rear of the power module. This is an important feature since the repair frequency within the engine room could be at least twice a year. Repair of a previously operated reactor, shield and NaK lines is considered impractical if not impossible due to high radiation levels around these components. However, the Manned Shuttle or Tug installation of a "cold" reactor can be accomplished without shut-down of the other reactor in the reference design, as radiation levels at the docking interface are about 13 mrem/hr. Replacement by manned vehicle of a "spent" reactor should only be accomplished a minimum of 10 days after its shutdown, to allow for radiation decay to tolerable levels.

RADIATION MONITORING AND CONTROL

Knowledge of the status of the crew's radiation exposure (accumulated and instantaneous doses) throughout the Space Base is a necessary part of the mission. The system must not only measure the absorbed dose and relative biological effectiveness of protons, electrons, photons and neutrons, but also measure these quantities at both skin and critical organ depths. Obviously no one monitoring system can meet all these criteria. Four separate systems appear to be required: (1) Passive Dosimetry, (2) Active Dosimetry, (3) Health Physics Instrumentation, and (4) Biological Dosimetry.

Frequent readout is required necessitating some readout in space. A reasonable system would require each crewman to have a Thermo-Luminescent Dosimeter rod connected with an identification card. Insertion into a special reader would give a daily readout on each individual which could be tabulated and analyzed by the on-board data management system.

Radiation control would be implemented by the use of several radiation instruments connected to alarms which can be programmed to signal the closing of doors and isolate ventilation systems. Decontamination techniques must be developed for application in zero-g and artificial-g modules.

An effective radiological monitoring and control program must incorporate a complement of trained personnel. It is estimated that in a crew of 50, an average time of at least 3 men are required to support the entire radiological control program. Personnel include a radiation safety officer assisted by the astronaut crew who have been crosstrained to allow them to make valid risk judgements and to function effectively in radiation emergencies. The presence of the reactors on a Space Base mission requires a minimum of additional support, the direct support of the reactors accounting for only 1/2 of a crewman out of the total of 3 required for the entire program.

2.7 SPACE BASE HAZARD SUMMARY

The specific potential radiological sources and hazards evaluated are summarized in Table 2-4 and are categorized in accordance with NASA Office of Manned Space Flight Safety Program Directive No. 1, Revision A.

2.8 REACTOR POWER MODULE STUDIES

Qualitative studies of nuclear safety implications concerned with reactor power module configurations and operation were performed. Configuration can be an important factor in providing nuclear safety. The servicing, replacement and operating characteristics of multiple reactor power modules are enhanced by providing adequate separation distances between power modules and between the Space Base core modules.

Several Power Conversion System (PCS) features can increase nuclear safety. The Brayton and organic Rankine cycles permit relatively low temperature operation which allows the use of non-liquid metal radiators. Toxic, corrosive and explosive coolants should be avoided where feasible. Multiple operating PCS units are preferred for safe shutdown and to minimize temperature transients. A separable heat exchanger at the reactor/PCS interface, allows for modular assembly and permits significant increases in the reentry ballistic coefficients, extending reactor orbital lifetimes by as much as a factor of 9.

Table 2.4. Space Base Radiation Hazard Categorization (Ground and Flight Personnel and Mission Hardware)

NORMAL CONDITIONS			MISSION PHASES			
Hazard Source	**Source Condition**	**Potential Hazard**	**Prelaunch**	**Launch/Ascent**	**Orbital Oper**	**End-of-Mission**
Natural Radiation Environment Geomagnetically Trapped Protons, Electrons and Galactic Cosmic Rays	Varying Degree of Intensity Depending on Orbit Position	Excessive Radiation	N/A	Neg	Neg	Neg
Solar Radiation	Solar Flare	Excessive Radiation	N/A	Neg - Marg	Neg - Marg	Neg - Marg
Reactor Power Module	Shutdown (No Operating History)	Excessive Radiation	Neg	Neg	Neg	N/A
	Shutdown (Post Operation)	Excessive Radiation	N/A	N/A	Neg	Neg
	Normal Operating Power	Excessive Radiation	N/A	N/A	Neg	N/A
		Thermal Interference	N/A	N/A	Neg - Marg	N/A
	Emergency Operating Power	Excessive Radiation	N/A	N/A	Neg - Marg	N/A
		Thermal Interference		N/A	Neg - Marg	N/A
Interfacing Vehicles *Reusable Nuclear Shuttle	Shutdown (Post Operation)	Excessive Radiation	N/A	N/A	Neg	N/A
	Normal Power (Thrusting)	Excessive Radiation	N/A	N/A	Neg	N/A
*Orbital Propellant Storage Depot (Reactor Power System	Shutdown (Post Operation)	Excessive Radiation	N/A	N/A	N/A	N/A
	Normal Operating Power	Excessive Radiation	N/A	N/A	Neg	N/A
Experiment Laboratories X-ray Equipments	As Installed	Excessive Radiation	Neg	N/A	Neg	N/A
Open Radioisotope Sources/Tracers	Stored	Excessive Radiation	Neg	Neg	Neg	Neg
	In Use	Radioactive Contamination	N/A	N/A	Neg	N/A
Closed Isotope Sources/Capsules	As Installed	Excessive Radiation	Neg	Neg	Neg	Neg
	As Installed	Excessive Radiation	Neg	Neg	Neg	Neg
ACCIDENT CONDITIONS						
Space Base Reactor Power Module	Damaged Reactor Shield	Excessive Radiation	Neg	Neg	Crit	Crit
		Tritium Release	Neg	Neg	Marg	Marg
	NaK Coolant Release	Excessive Radiation (Activated NaK)	Neg	Neg	Neg - Marg	Neg - Marg
		Structural Corrosion	Neg	Neg	Neg - Crit	Neg - Crit
		Equipment Contamination	Neg	Neg	Neg - Crit	Neg - Crit
		Personnel Contamination	Neg	Neg	Neg - Crit	Neg - Crit
	Fission Product and NaK Coolant Leak	Excessive Radiation	Neg	Neg	Neg - Crit	Neg - Crit
		Structural Corrosion	Neg	Neg	Neg - Crit	Neg - Crit
		Equipment Contamination	Neg	Neg	Neg - Crit	Neg - Crit
		Personnel Contamination	Neg	Neg	Neg - Crit	Neg - Crit
	Non-Destructive Excursion	Excessive Radiation	Marg	Marg	Marg	Marg
	Destructive Excursion	Excessive Radiation	Crit - Cat	Crit - Cat	Crit - Cat	Crit - Cat
		Structural Corrosion	Crit - Cat	Crit - Cat	Crit - Cat	Crit - Cat
		Equipment Contamination	Crit - Cat	Crit - Cat	Crit - Cat	Crit - Cat
		Radioactive Debris	Crit - Cat	Crit - Cat	Crit - Cat	Crit - Cat
Interfacing Vehicles *Reusable Nuclear Shuttle	Fission Products in Plume	Excessive Radiation	N/A	N/A	Neg	Neg
	Reactor Disassembly	Excessive Radiation	N/A	N/A	Marg	N/A
	Loss of Attitude Control	Excessive Radiation	N/A	N/A	Marg	N/A
*Orbital Propellant Storage Depot	(Same as Space Base Reactor Power System)	(Same as Space Base Reactor Power System)	N/A	N/A	Marg	N/A
Experiment Laboratories X-ray Equipment/ Dynamic Generators	Inadvertent Turn-On	Excessive Radiation	Neg - Marg	N/A	Neg - Marg	Neg - Marg
Isotope Tracers/ Open Sources	Release to Space Base Environment	Internal Exposure of Critical Body Organs	N/A	N/A	Neg - Cat	Neg - Cat
Closed Sources/ Isotope Capsules	Shielding Failure/ Removal	Excessive Radiation	Neg - Marg	Neg - Marg	Neg - Marg	Neg - Marg
	Encapsulation Failure	Internal Exposure of Critical Body Organs	N/A	N/A	Neg - Marg	Neg - Marg

*Prelaunch and launch of these vehicles is not included.

Legend.
N/A - Not Applicable
Neg - Negligible
Marg - Marginal
Crit - Critical
Cat - Catastrophic

The Zirconium Hydride (ZrH) thermal reactor exhibits several inherent safety features which may not be available in a fast reactor. These include: (1) a desirable negative temperature coefficient providing a means of self shutdown, (2) compact (minimum) void space, reducing fuel load susceptibility to core compaction accidents and (3) release of hydrogen within the core upon a temperature excursion providing inherent shutdown capability. Conversely, however, the ZrH reactor is moderated by hydrogen and immersion in hydrogeneous materials, such as water, can cause reactivity increases resulting in potential excursions or quasi-steady state operation. Positive and permanent shutdown after operation has been recommended. Neutron poison injection coupled with control drum lockouts are feasible techniques.

2.9 SAFETY GUIDELINES

A number of guidelines have resulted from the study and are delineated in Vol V, Part 1. Reference shall be made to this document and supporting data in the implementation of nuclear safety guidelines for subsequent phases of the Manned Space Flight program. Several of the significant guidelines are summarized in Table 2-5.

2.10 TECHNOLOGY IMPLICATIONS

Areas for further study and where technological improvements are required include:

- Launch support requirements for the handling, processing and storage of nuclear hardware.
- Liquid metal support requirements at the launch center including launch complex fire protection.
- Nuclear reactor/power module separation techniques.
- The impact and contingency actions required for nuclear debris around a Space Base and in space.
- Analyses and test program to determine adequacy of a LiH shield as a reentry material before and after operation in a space and radiation environment.
- Methods of dissipating reactor waste heat without degradation of shield material (loss of hydrogen).

- Development of blast and fragmentation models and protection schemes for protection of nuclear hardware (particularly isotope systems) during a launch vehicle explosion at the launch pad.

- Definition of permanent reactor shutdown systems.

- Development of in-orbit decontamination techniques for zero-g and artificial-g applications.

- Development of space qualified in-orbit radiation monitoring equipment.

- Standardization of Safety Analysis techniques.

Table 2-5. Safety Guidelines Summary

DESIGN FEATURES

1. Provide special nuclear assembly and storage facilities capable of segregating isotope and reactor storage and checkout activities
2. Nuclear storage and checkout facilities must be provided with proper environmental control and design features to reduce liquid metal fire hazard potential
3. Provide redundant cooling capability for isotopes during storage, checkout, transportation and at the launch pad
4. Where feasible, consider use of non-liquid metal radiators
5. Provide a universal transporter in support of transportation and prelaunch activities
6. Provide for the use of the Space Shuttle as the prime and/or backup means of launch and/or recovery of nuclear hardware
7. Provide Storm Shelter facilities for refuge from Solar Flare events
8. Provide on-board radiological monitoring of radiation dose accumulated by the crew
9. Select subsystem components and component piece parts with higher than average performance to minimize the effects of degradation due to radiation over the mission duration
10. Provide orbit adjust capability to rapidly change Space Base orbit altitude in the event of a severe nuclear incident in orbit
11. Provide separate waste management systems for crew and laboratory contaminated waste
12. Provide for detached module implementation of gamma ray and neutron sensitive experiments
13. Provide shielded storage (approximately 20 g/cm^2) for photographic film and emulsions
14. Locate laboratories using relatively large isotope tracer concentrations in zero-g and possible isolatable and removable portions of the vehicle
15. Provide a positive mechanical system for separation of the reactor power module from the Space Base
16. Provide fragmentation and impact protection for nuclear hardware
17. Design reactor to preclude criticality accidents and destructive excursions
18. Provide positive means of sensing reactor control drum position
19. Provide puncture and rupture protection for NaK coolant lines (double containment features)
20. Provide an effective reactor reentry and impact protection system

SAFETY DEVICES

1. Provide anti-criticality and penetration-free containment for nuclear hardware
2. Provide control drum lock-out devices for reactor power modules
3. Consider use of dummy power module for integration tests in VAB
4. Provide compatible liquid metal fire protection and fighting capability wherever liquid metals are present
5. Provide radiation and thermal shields for prolonged operations around a large isotope heat source.
6. Provide multiple escape routes for personnel in radiation hazard areas
7. Consider use of liquid metal sump tanks to isolate and contain liquid metal leaks in prime hardware
8. Consider safing of the S-II destruct system as Eurasian overfly is made
9. Provide means of safing a reactor and terminating a quasi-steady state critical condition
10. Provide rapid response recovery, safing and decontamination capability over entire potential impact zone
11. Provide emergency EVA suits compatible with a NaK environment
12. Provide shielding and control interlocks and restrict reorientation of dynamic radiation generators (x-rays, ion guns, lasers and microwave sources)
13. Provide an effective and automatic means of reactor shutdown under all conditions
14. Provide for positive and permanent reactor shutdown prior to disposal or recovery
15. Provide for the safe and prompt disposal or recovery of a spent or malfunctioning reactor
16. Provide tracking and location aids for land and water recovery of nuclear hardware

WARNING DEVICES

1. Provide personnel dosimetry, radiation monitoring, warning signs and instrumentation in all areas where nuclear hardware is present
2. Provide proper escort and warnings during transportation
3. Provide rapid response fire alarm and detection systems for liquid metal fires
4. Provide proper liquid metal fire fighting materials with yellow markings
5. Provide integrated dose, nuclear system status and fault diagnostic support in orbit and at the Mission Control Center (MCC)
6. Provide ground supported advanced warnings of malfunctions or hazardous conditions where possible (solar flare event, etc)
7. Provide a central on-board warning system for monitoring and altering against radiological hazards
8. Provide proper governmental authorities with technical data for advanced warnings and preparations required for impending ground impact of nuclear material
9. Provide means for monitoring and warning of imminent collisions with space debris and orbiting vehicles
10. Provide instrumentation to detect a LiH reactor shield puncture
11. Provide for liquid metal leak detection during prelaunch and in orbit

SPECIAL PROCEDURES

1. Select routes to avoid heavily travelled and populated areas in the transport of nuclear hardware
2. Use cross-trained personnel in support of nuclear hardware prelaunch activities with actual real situation experience (radiation and liquid metal hazards)
3. Limit and regulate personnel/activities in radiation areas
4. Restrict use and presence of ordnance and disposal rocket motors within nuclear facilities.
5. Perform reactor criticality checks prior to delivery to launch site (KSC)
6. Limit criticality testing to provide negligible fission product inventory during prelaunch
7. Employ two man "buddy" system in hazardous areas
8. Install reactor power modules and isotopes systems as late in the prelaunch sequence as feasible
9. Provide appropriate procedural modifications in the KSC Ground Safety Plans and the USAF Range Safety Manual
10. Keep nuclear hardware operations at the launch pad to a minimum
11. Maintain control drum lockouts in position during prelaunch operations Restrict control drum movement to a single drum
12. Conduct thorough evaluation of the necessity and desirability of integration and testing of nuclear reactor power modules within the VAB
13. Prohibit smoking and eating in designated radiation and liquid metal areas
14. Maintain current administratively controlled areas with a minimum radius of approximately 13 km and exclusions areas of 4 km radius
15. Consider limiting flight termination impact areas to outside the continental shelf
16. Provide continuous attended support by the MCC for warning, radiological control and fault diagnosis
17. Establish crew rotation procedures in conformance with career and periodic dose guidelines
18. Restrict EVA during orbits intercepting the South Atlantic Anomaly
19. Restrict approach paths of vehicles employing IR (infrared) sensors to avoid interference from high temperature sources.
20. Establish minimum rendezvous distances and shielded approach corridors to orbital vehicles employing nuclear power systems to minimize exposure of crew
21. Provide experiment data screening procedures for experiments sensitive to South Atlantic Anomaly interference.
22. Minimize power level on operating reactors during reactor replacement.
23. Restrict repairs to NaK lines in space (repair is not considered feasible)

SECTION 3
REFERENCE SPACE BASE PROGRAM

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SECTION 3
REFERENCE SPACE BASE PROGRAM

3 1 GENERAL

The primary purpose of using a reference Space Base program is to establish configuration and characteristics which allow identification, analysis and evaluation of potential nuclear related hazards and means of reducing or eliminating these hazards. In addition, this reference definition provides a design against which the guidelines and considerations, resulting from the study, can be evaluated and applied for future missions.

A Space Base is defined to be a centralized earth-orbital facility for the conduct of multi-disciplinary research, development and operations. The vehicle is envisioned to be operational over a period of ten (10) years. The crew will consist of nominally 50 men whose tour of duty may be up to one year.

A Space Base program includes the complete operation of a Space Base, including orbital logistic support, interfaces with other orbiting vehicles and mission support.

The following sections summarize those aspects of a Space Base program which are of particular importance to the evaluation of the nuclear hazards as well as the interpretation of the results. The key assumptions and data sources used in establishing this reference program are presented in the following sections.

3.2 SPACE BASE VEHICLE CHARACTERISTICS

3.2.1 SPACE BASE CONFIGURATION

The Space Base configuration used in the study was based on the Phase A conceptual designs developed by McDonnell Douglas for NASA-MSFC and North American Rockwell for NASA-MSC. These designs are described in References 3-1 and 3-2, respectively. Figure 3-1 illustrates the respective Space Base configurations. Both configurations are similar; however, the counter-rotating artificial "g" sections allow the MDAC configuration to assume any

orientation with respect to the orbit plane. It was assumed that the reference design has this capability and, therefore, interfacing vehicles could be exposed to a variety of reactor nuclear radiation environments. (See Section 3.8.2)

Both configurations are similar in overall dimensions, subsystems, and experiments employed. Therefore, for purposes of the study, it was feasible to define a single reference Space Base program which incorporates those features of both concepts that are significant from the standpoint of nuclear system safety. The Space Base configuration and its key dimensions used in the study are shown in Figure 3-2. This figure also indicates docking locations for attached and detached (free flying) experiment modules as well as logistic vehicles.

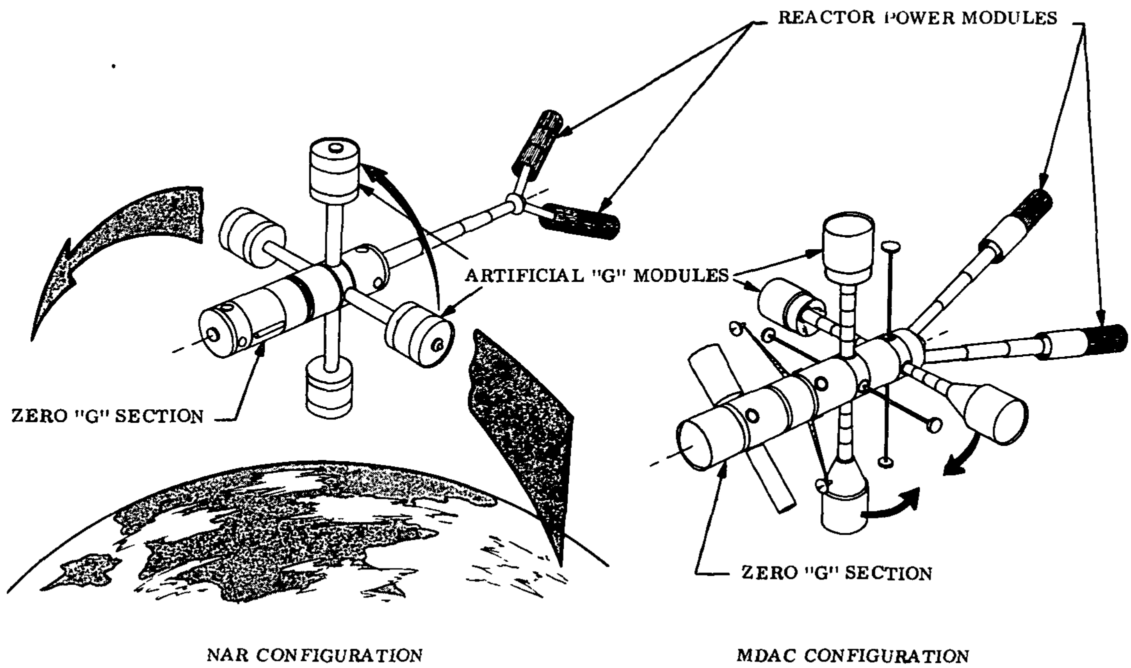
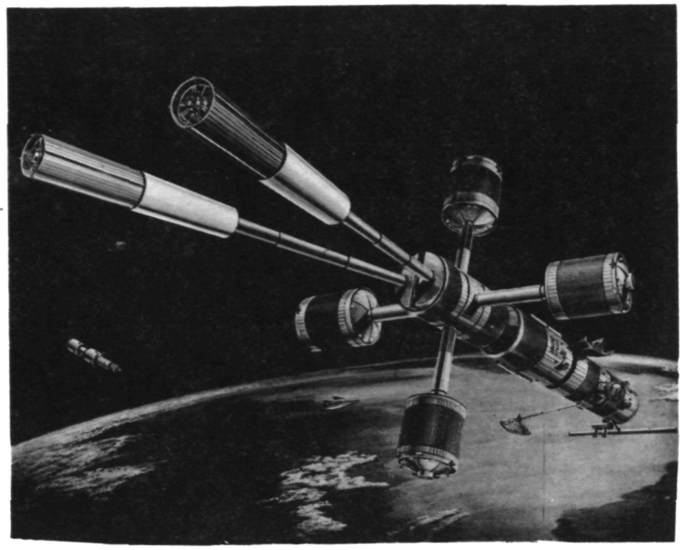
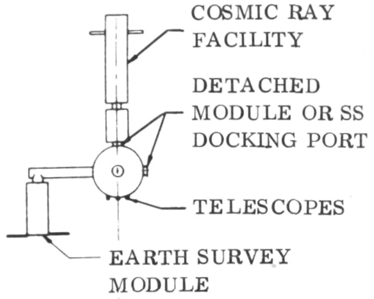


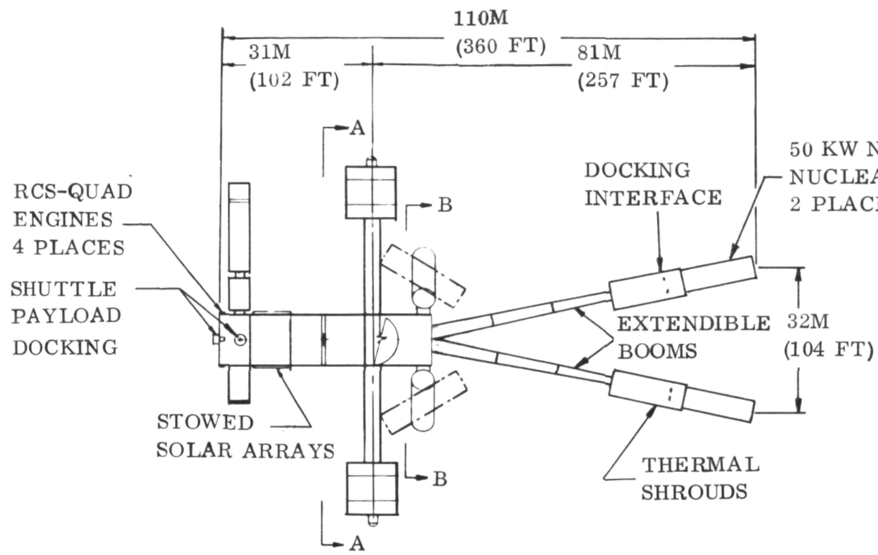
Figure 3-1. Space Base Configurations

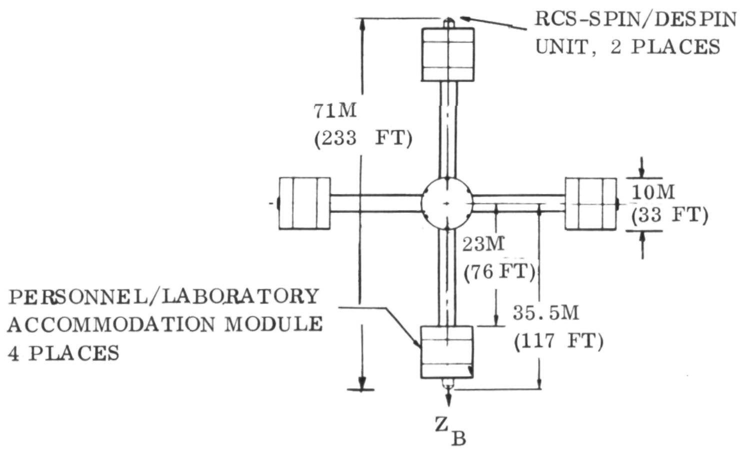
3.2.2 SPACE BASE SYSTEMS/ SUBSYSTEMS

The systems used to implement the Space Base are of interest from the standpoint of their susceptibility to damage from nuclear radiation and also the nuclear hazard sources they might contain. Since the Space Base Electrical Power System includes nuclear reactors, this system is of particular interest. The nuclear sources and their locations are listed in Table 3-1.









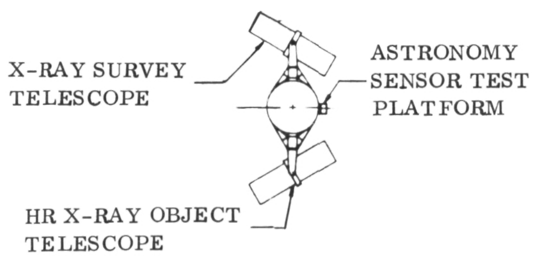


Figure 3-2. Representative Space Base Configuration Characteristics

KEY CONFIGURATION AND MISSION CHARACTERISTICS

• CONFIGURATION	ZERO-G AND ARTIFICIAL G 10M (33 FT) DIA MODULES. POWER MODULES ON EXTENDABLE BOOMS OF ZERO-G CORE.
• POWER REQUIREMENT	100 KWe
• REACTOR SYSTEM	2-ZH REACTOR-BRAYTON POWER MODULES, EACH WITH 330 KWT (50 KWE) NOMINAL RATING EMERGENCY OPERATION - 600 KWT EACH
• LAUNCH VEHICLE	SATURN INT-21, KICKSTAGE AND SPACE SHUTTLE
• LOGISTIC SUPPORT	SPACE SHUTTLE AND SPACE TUG
• LAUNCH TRAJECTORY	46° LAUNCH AZIMUTH FROM KSC, EURASIAN OVERFLY
• ORBIT	500 KM (273 NM) 55° OR 30° INCLINATION ALTERNATE
• LIFETIME	10 YEAR-MISSION, 5 YEAR-REACTOR DURATION, 2.5 YEARS-POWER CONVERSION SYSTEM
• CREW SIZE	50 (NOMINAL) WITH 90 TO 180 DAY CREW ROTATION
• EXPERIMENTS	MUTIDISCIPLINED ON-BOARD AND FREE FLYING SUBSATELLITE PROGRAM
• POWER MODULE DISPOSAL	BOOST BY INTEGRAL DISPOSAL SYSTEM TO 990 KM HIGH ALTITUDE ORBIT
• REACTOR SHIELD	SHAPED 4π LITHIUM HYDRIDE NEUTRON SHIELD, TUNGSTEN GAMMA SHIELD
• RADIATION ENVIRONMENT	1 MREM/HR MAX. FROM REACTORS PLUS NATURAL RADIATION ENVIRONMENT
• INTERFACING VEHICLES	SUBSATELLITES, SPACE SHUTTLE, TUG, RNS, OPSD.

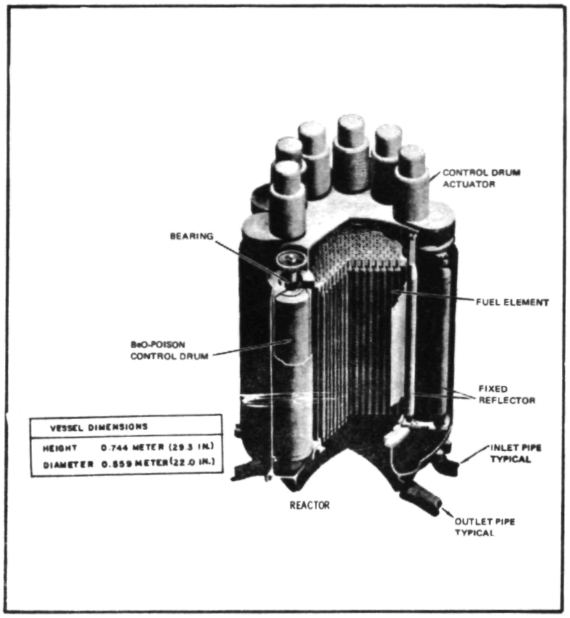
Table 3-1 Space Base Program Nuclear Sources

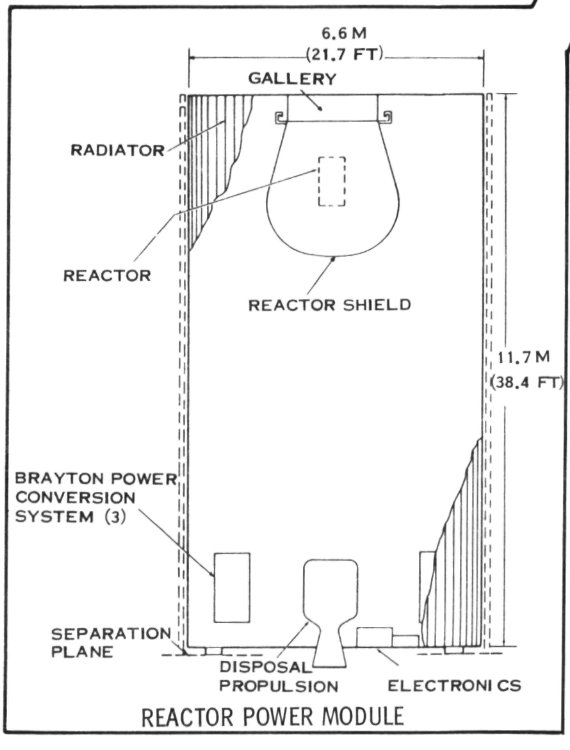
	Nuclear Sources	Remarks
Baseline	Reactor(s)	Space Base Nuclear Shuttle (Interfacing Vehicle) Orbital Propellant Depot (Interfacing Vehicle)
	Radioactive Tracers	Experiment Laboratories (On-Board)
	X-Ray Equipment	Experiment Laboratories (On-Board)
	Natural Environment	Earth Trapped/ Cosmic Radiation, Solar Flare
Potential Additions	Isotope Brayton Power	Back-up Electrical Power Candidate (On-Board)
	Radioisojet Thrusters	Orbit Adjust System (On-Board)
	Isotope Heated Waste Management System	Advanced Technology Experiment and/ or Operational System (On-Board)

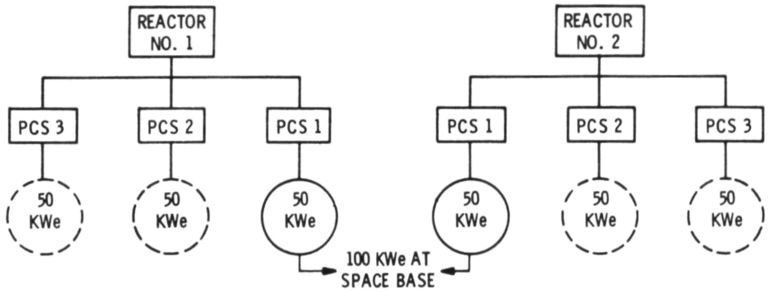
3.2.2.1 Electrical Power System

The primary Electrical Power System of the Space Base is required to provide 100kWe. The Electrical Power System includes the Reactor/ Brayton Cycle energy conversion equipment, reactor disposal equipment, associated power conditioning equipment, radiators, thermal shrouds and back-up electrical power supply. With the exception of the power distribution equipment and the back-up power supply the electrical power system is packaged in two separate "power modules" located at the end of extendable booms approximately 60 meters from the habitable Space Base core modules.

Figure 3-3 shows the Reactor Power Module configuration used in the study analyses. Figure 3-4 shows the schematic of the Brayton cycle energy conversion equipment and indicates the cycle characteristics (temperature, power level, coolant, etc.). The reactor thermal power level during operation is one of the most important characteristics of the energy conversion system since this parameter affects the shielding required, coolant activation and fission product inventory. For this analyses it has been assumed that each reactor normally operates at 330 kWt to provide 50 kWe from each module. It has also been assumed that an alternate (contingency) power mode is available whereby a single reactor is

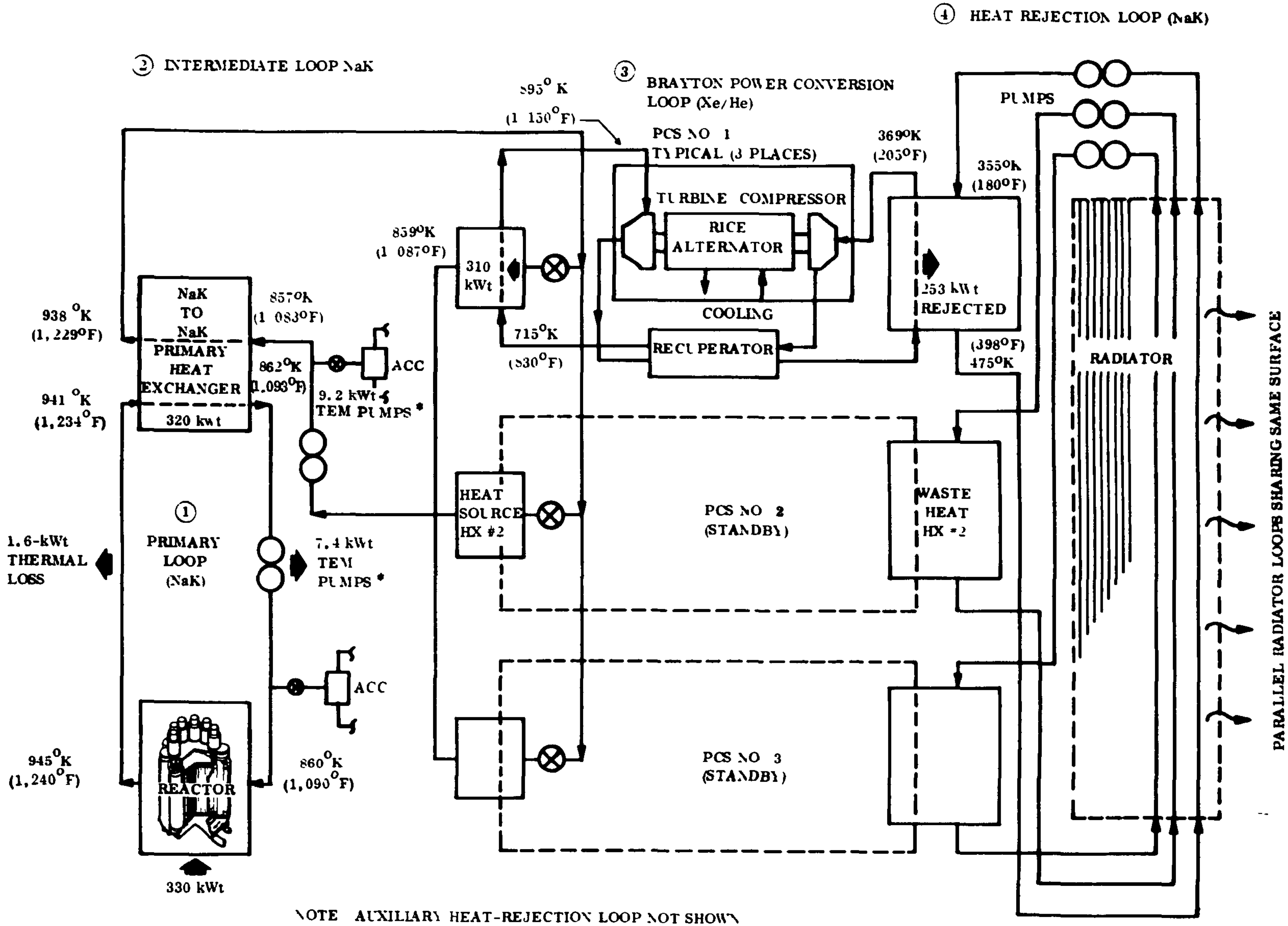






ITEM	CONCEPT REMARKS
REACTOR	2 ZrH, 295 FUEL ELEMENTS
CONTROL	10 DRUMS
POWER CONVERSION	3-50 KW_E BRAYTON UNITS/REACTOR
NORMAL POWER LEVEL	330 KW_T
EMERG POWER LEVEL	600 KW_T (ASSUMED FOR STUDY)
SHIELD	SHAPED 4 π LiH
RADIATION LEVELS	1 MR/HR SB INTERFACE
LIFETIME	5 YEARS

Figure 3-3. Reactor Power Module Details



NOTE AUXILIARY HEAT-REJECTION LOOP NOT SHOWN

*THERMOELECTRIC ELECTROMAGNETIC (TEM) PUMPS ARE IN THE SYSTEM PER REFERENCE 2-1. MORE RECENT CONCEPTS EMPLOY ELECTROMAGNETIC (EM) PUMPS.

Figure 3-4. Schematic of Reactor/ Brayton Cycle System

operated at 600 kWt, producing the total electrical requirement of 100 kWe for short periods. This mode could be utilized when one reactor had been shut down for replacement or maintenance (Reference 3-2).

A more detailed description of the Reactor Power Module, its Brayton cycle energy conversion system and disposal system can be found in Volume III, Part 1. The characteristics of the nuclear hazards associated withthe reactor power modules are discussed in Section 3.8.2 of this Volume. Consideration of Reactor Power Module maintenance and repair, and disposal techniques are found in Sections 7.3.3 and 7.3.4.

The back-up electrical power subsystems considered include solar cell and fuel cell energy conversion. The possibility of using an isotope-Brayton power system is also considered in this study (Reference 3-3 and 3-4).

3.2.2.2 Other Systems

The other systems of the Space Base are not defined in detail in this section because they do not contain large nuclear sources but are of interest due to the effects radiation has on their operation during the mission.

Table 3-2 shows the nomenclature adopted for designation of the Space Base systems and the corresponding nomenclature used in the Phase A design definition studies (References 3-1 and 3-2). This nomenclature is used in referring to the respective systems/ subsystems for evaluation of radiation exposure sensitivity in Section 4, and in establishing design, operational and procedural considerations in Section 6. Section 4.3 contains a breakdown of generic components associated with each subsystem. Appendix A of this Volume, "Radiation Exposure Limts," contains a further discussion of system and subsystem components.

3.3 EXPERIMENT PROGRAM

The experiment program used in the analyses is based primarily on Reference 3-5 and is supplemented with data from Reference 3-6. These experiments are considered representative of the types of endeavors that would be undertaken in the various scientific disciplines associated

Table 3-2. Equivalent System Nomenclature

Reference System Nomenclature	NAR Nomenclature	MDAC Nomenclature
Electrical Power	• Electrical Power	• Electrical Power
Environmental Control	• Environmental Control and Life Support	• Environmental Control and Life Support
Communications and Data Management	• Information	• Communications • Data Management • On-Board Checkout
Navigation and Control	• Guidance and Control • Propulsion and Reaction Control	• Stabilization and Attitude Control • Guidance and Navigation • Propulsion
Protection	• Crew and Habitability • Environmental Protection	• Crew Habitability and Protection
Docking	• Docking	• Mechanical

with a Space Base program. Information concerning radiological hazard sources within the detached experiment modules and the on-board experiment laboratory is contained in Sections 3.8.3.3 and 3.8.4, respectively.

3.4 SPACE BASE CREW

The nominal Space Base configuration described in Section 3.2 is capable of accommodating 48 to 60 crewmen. The nominal tour of duty is 90 to 180 days. Crew rotation of up to 12 months as affected by radiological considerations is treated parametrically in the analysis of Sections 6.3.1.2 of this Volume.

3.5 INTERFACING VEHICLES

Figure 3-5 illustrates the mission interrelationships of the interfacing vehicles with the Space Base and other space programs.

3.5.1 SPACE TUG

The Space Tug interfaces with all vehicles in the Space Base program. Although the Space Tug contains no nuclear sources, it is a candidate vehicle to assist in reactor disposal and replacement (see Sections 7.3.3 and 7.3.4) and in deployment of nuclear hardware delivered by the Space Shuttle. A preliminary defintion of a representative Tug configuration and operation can be found in Reference 3-7.

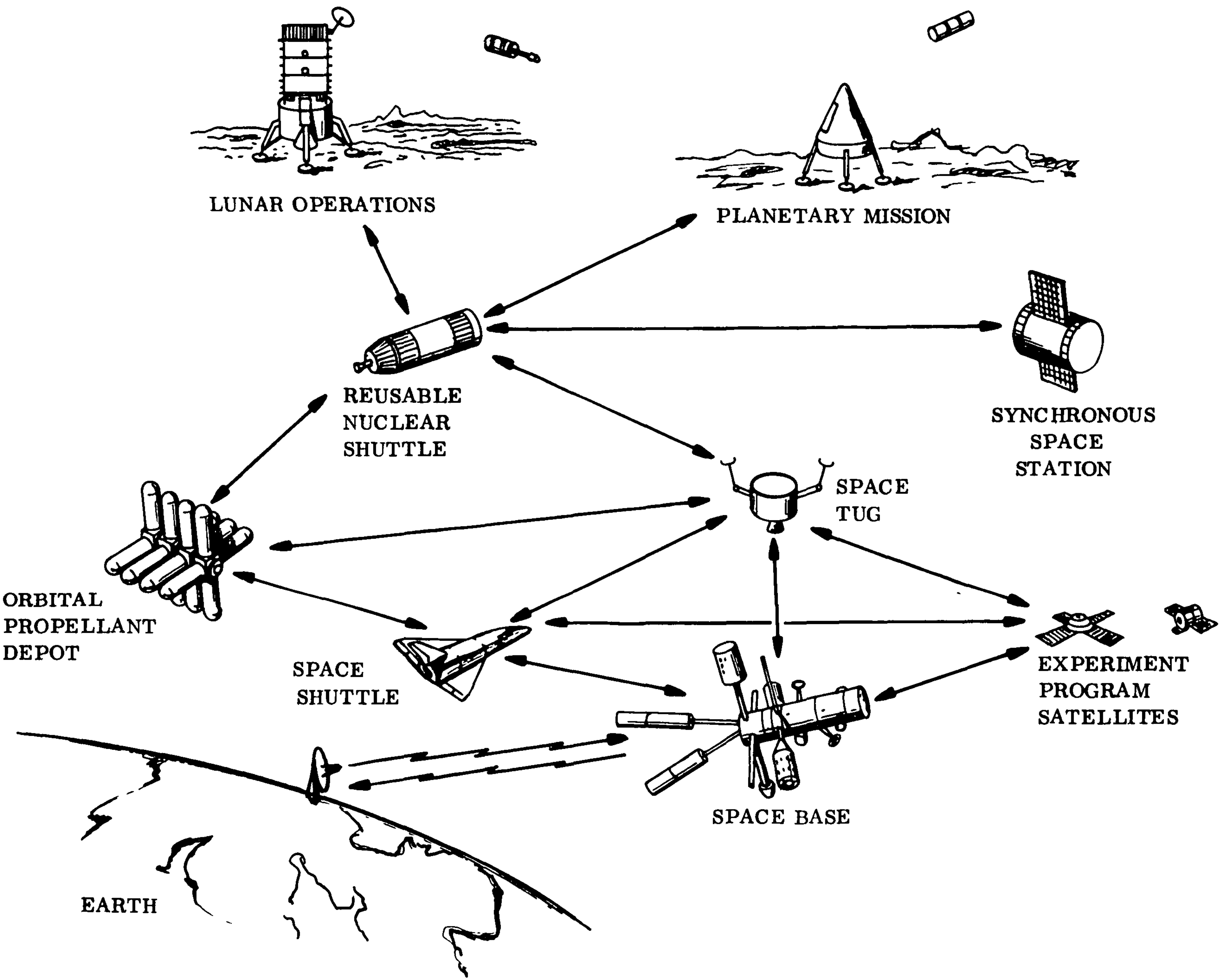


Figure 3-5. Potential Space Base Program Interfacing Vehicles

3 5.2 SPACE SHUTTLE

The Space Shuttle is the logistic vehicle for the Space Base. In this capacity it may be employed to deliver replacement reactor power modules and dispose of spent modules. The shuttle will also serve as a means for disposal of isotope systems during End-of-Mission Operations. The nuclear safety implications of these Shuttle missions are addressed in Volume IV. References 3-8 and 3-9 describe candidate Shuttle configurations and operations.

3 5.3 REUSABLE NUCLEAR SHUTTLE

The Reusable Nuclear Shuttle (RNS) is the logistic vehicle which could service other space facilities from earth orbit such as the Lunar Orbiting Space Station. It may also serve as the propulsion system for interplanetary missions. A Space Base could provide an orbital support facility for RNS payload assembly and maintenance operations. The RNS (Reference 3-10) is powered by a Nerva nuclear rocket engine and is therefore a potential radiation source when in the vicinity of the Space Base. (See Section 3. 8. 3.)

3 5 4 ORBITAL PROPELLANT STORAGE DEPOT

The Orbital Propellant Storage Depot (OPSD) may be required to store propellant to service the RNS and other vehicles. Although definition of this vehicle is not complete, it is presumed that one of the concepts employs a nuclear reactor in its Electrical Power System. Therefore, the OPSD represents a potential nuclear source to be considered. (See Section 3. 8. 3.)

3.5.5 DETACHED EXPERIMENT MODULES

Detached Experiment Modules carry experiment equipment which must be located away from the Space Base due to such considerations as stringent stability requirements, the need to achieve an unobstructed view of space or avoidance of Space Base effluents and Space Base interactions. An additional consideration is the sensitivity of these experiments to the radiation environment created by the Space Base (See Section 6. 3. 1.4.) Such "free flying" modules may serve several of the Space Base experiment disciplines and may vary considerably in electrical power requirements (Reference 3-11). The reference power supply for these vehicles is the solar array; however, radioisotope generators have been considered as candidate power sources for some applications and would represent an additional radiation source associated with the Space Base Program. (See Section 3. 8. 3.)

3.6 LAUNCH FACILITY

The Kennedy Space Center (KSC), Launch Complex 39, is the reference launch facility (Reference 3-12) which is assumed to include the Industrial Area, the Vehicle Assembly Building, Launch Pad A and B and supporting facilities and servicing equipment.

3.7 SPACE BASE PROGRAM MISSION

The Space Base program mission is defined to begin with the arrival of the flight hardware at the launch facility and culminates with the disposal of the program nuclear hardware at its end of life or completion of the Space Base mission.

3 7.1 LAUNCH/ TRAJECTORY/ ORBIT PARAMETERS

The launch vehicle for Space Base modules is the INT-21 (a two stage Saturn V with a modified instrumentation unit). Both direct ascent and Hohman transfer techniques have been considered for final orbit insertion. Table 3-3 shows the launch and orbit parameters for candidate orbits. The mission orbit inclination is 55 degrees. An alternate orbit of 30 degrees inclination is also considered to indicate the variation in the natural radiation environment with inclination. (See Section 3.8.1.)

3.7.2 MISSION PHASES

In order to evaluate the varied conditions and operations of the Space Base program, four mission phases have been defined, as shown in Table 3-4. Each phase has been broken down into appropriate subphases and operations. Appendix B of this volume presents a detailed description of the various phases. The following sections identify the major assumptions or conditions of each phase.

Table 3-3. Launch and Orbit Parameters

	Mission Orbit	Alternate Orbit
Altitude	500 km (273 nm)	500 km (273 nm)
Inclination	50°	30°
Launch Azimuth	Possible 46° (TBD)	77° to 103°
Launch Complex	KSC	KSC
Hohman Parking Orbit	185 x 500 km (100 x 273 nm)	185 x 500 km (100 x 273 nm)

Table 3-4. Space Base Program Mission Phases

Phase	Activities	Characteristics
4 0 END OF MISSION	• POWER MODULE DISPOSAL SEPARATION TRANSFER TO HIGH ORBIT • SPACE BASE CLOSEOUT CONTINGENCY PLANS RECOVERY	POWER MODULE - 990 KM ORBIT ISOTOPES - RECOVERY SHUTTLE
3.0 ORBITAL OPERATIONS	• ORBITAL BUILDUP • CHECKOUT • START-UP • OPERATIONAL MODE • CONTINGENCY OPERATION	BUILD-UP 105 WEEKS 10 YEAR MISSION POWER MODULE REPLACEMENT - 5 YR SHUTTLE RESUPPLY EXPERIMENTATION 50 CREW (ART G AND ZERO G) INTERFACING VEHICLE SUPPORT
2.0 LAUNCH/ASCENT	• LAUNCH • S-IC BOOST • S-II BOOST • RENDEZVOUS AND DOCKING	INT-21 BOOSTER SINGLE OR DUAL REACTOR LAUNCH SHUTTLE SUPPORT LAUNCHES 500 KM x 55^0 OR 30^0 INCL ORBIT EURASIAN OVERFLY
1.0 PRELAUNCH	• TRANSPORTATION • RECEIPT, INSPECTION, STORAGE • CHECKOUT AND ASSEMBLY • INTEGRATION • COUNTDOWN	3 POWER MODULES AT KSC 90 DAY CHECKOUT PERIOD COLD REACTOR INTEGRATION LATE IN SEQ. KSC COMPLEX 39

3 7.2.1 Prelaunch

The Prelaunch Phase encompasses the period from arrival of the flight hardware at the launch facility through to completion of the countdown which terminates in initiation of first stage boost. In evaluating radiological hazards associated with a reactor it is important to know the reactor operating history prior to receipt at the launch complex. This history determines the radiation field around the reactor and the fission product inventory. For this study it is assumed that operation of the reactor is restricted to low level criticality checks such that total energy release is approximately 30 kW-hour at a thermal power level of about 100 watts. Section 3.8.2 further discusses the radiological characteristics of the reactor after low level criticality checks.

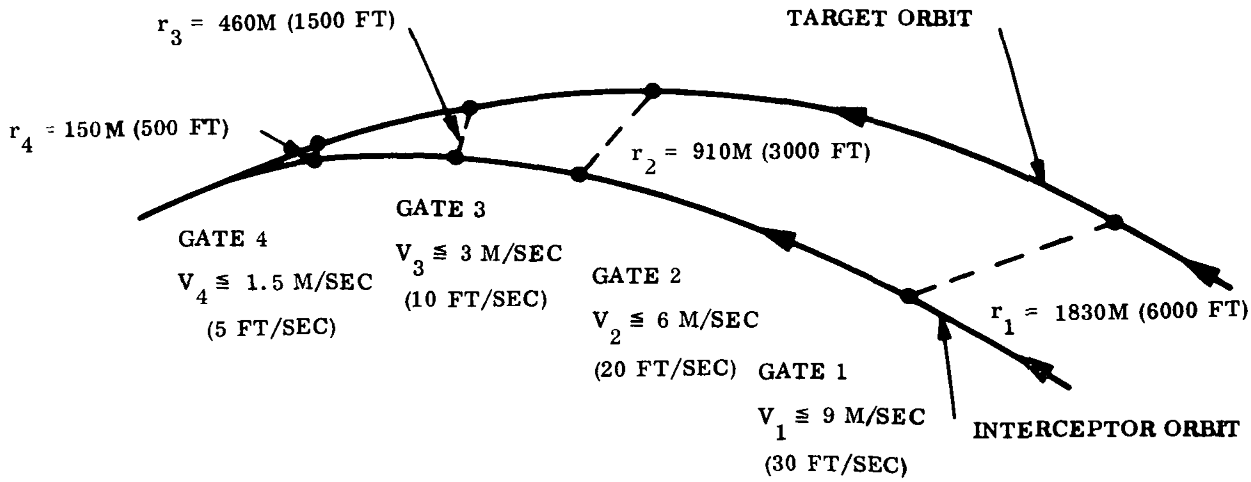
3.7.2.2 Launch/ Ascent

The Launch/ Ascent Phase is assumed to cover that period from the initiation of the first stage boost, through rendezvous and docking with the Space Base. Vehicles which rendezvous with an operational Space Base will be exposed to radiation from the Reactor Power Modules. In order to assess the potential degree of radiation exposure (integrated dose), it is necessary to know the approach path and the velocity relative to the Space Base as a function of position from the final docking area. Figure 3-6 shows the normal terminal rendezvous braking gates used in this study (Reference 3-1). These gates are assumed to apply to all vehicles which dock with the Space Base as previously discussed in Section 3.5.

3.7.2.3 Orbital Operations

The Orbital Operations Phase begins with the build-up of the Space Base, continues through attainment of full operating potential and terminates at the close-out of the Space Base.

During this phase the Space Base operations are carried out which implement the experiment program, maintain operational capability and support activities with other programs (e.g., interplanetary, lunar space station, etc.). This orbital operations phase covers a period of approximately 10 years. During this time it will be necessary to replace the reactor power modules and periodically resupply expendables, update prime hardware and rotate the crew. Reactor replacement is assumed to be required after five years of operation at the 330 kWt power level. Space Shuttles will provide the necessary logistic support.



NOTE BRAKING GATE ΔV'S APPLIED ALONG LINE-OF-SIGHT

Figure 3-6. Terminal Rendezvous Braking Gates

3.7.2.4 End-of-Mission

The End-of-Mission Phase deals with shut-down of the Space Base facility and/ or disposal or recovery of nuclear hardware. Disposal and/or recovery of the reactor power modules and the isotope sources are the prime considerations in this study.

The prime power module disposal technique employed in the study is boosting the power module to a long-life, earth orbit. Reactor power module disposal is discussed in Section 7.3.4. The handling of isotopes is treated in Section 7.3.2.

3.8 RADIOLOGICAL SOURCE CHARACTERISTICS

Major sources of radiation associated with a Space Base program as shown previously in Table 3-1 eminate from: (1) The Natural Environment, (2) The Space Base (Reactor) Power Modules, (3) Interfacing Vehicles, and (4) Experiment Laboratories within the Space Base. The following sections define the source characteristics used in Section 6.3 to evaluate

biological exposure, subsystem and equipment degradation, and experiment interferences. The natural environment data is presented for the reference 55 degree inclination orbit. Section 3.8.1.4 discusses the variation that would be encountered at the 30 degree inclination orbit.

3.8.1 NATURAL RADIATION ENVIRONMENT

The natural radiation environment encountered in the 55 degree inclination orbit is due primarily to geomagnetically trapped protons and electrons, galactic cosmic radiation and solar flares. Note: Although natural environment data in precisely the reference orbit altitude was not always available in the literature, the data utilized in the study is within 15 km of reference altitudes and introduces negligible error.

3.8.1.1 Biological Exposure

Figure 3-7 shows the combined daily radiation dose rate as a function of the vehicle cylindrical wall thickness due to the combination of geomagnetically trapped protons, electrons, and galactic cosmic radiation (Reference 3-13). This is the averaged hourly dose rate that would be experienced continuously by the crew and biological specimens while on board the Space Base. The averaged rate includes the contribution from the geomagnetically trapped radiation in the South Atlantic Anomoly where the peak flux could be as high as 36 rem/ hour. The galactic cosmic radiation contribution is considered a constant, and not a function of cylinder wall thickness, since the shielded dose including secondary radiation, is small compared to the geomagnetically trapped radiation (Reference 3-14).

Figure 3-8 shows the expected dose again as a function of cylinder wall thickness, from a single solar flare event. These events may last from a few hours to several days with peak intensities of $\sim$ 3 rem/ hour. The model for solar flare event occurrence is shown in Figure 3-9. Both of these figures are derived from Reference 3-13. A crewman performing EVA without the added protection of the nominal 1.6 g/ cm^2 wall thickness would experience dose rates to the skin at least a factor of 2 higher. Reference should be made to Section 6.3.1.2 for an analysis of this situation.

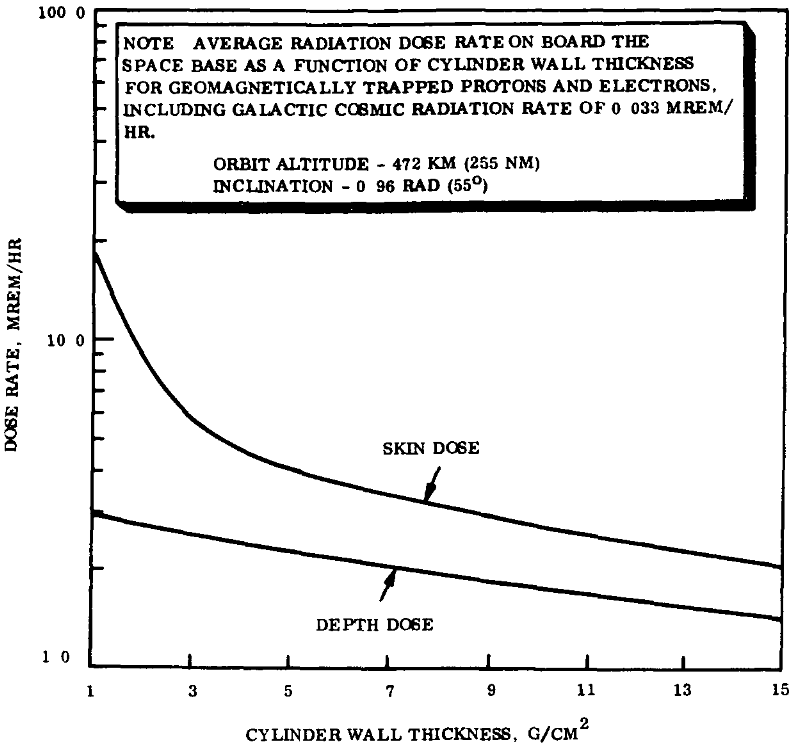


Figure 3-7. Averaged Radiation Dose Rate On-Board the Space Base From Natural Space Radiation

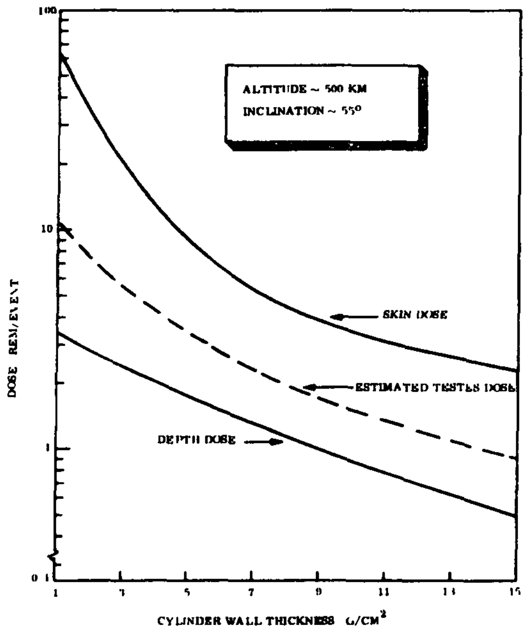


Figure 3-8. Solar Particle Event Radiation Dose at 475 - 530 km (255 - 285 nm), 50° - 57° Circular Orbits

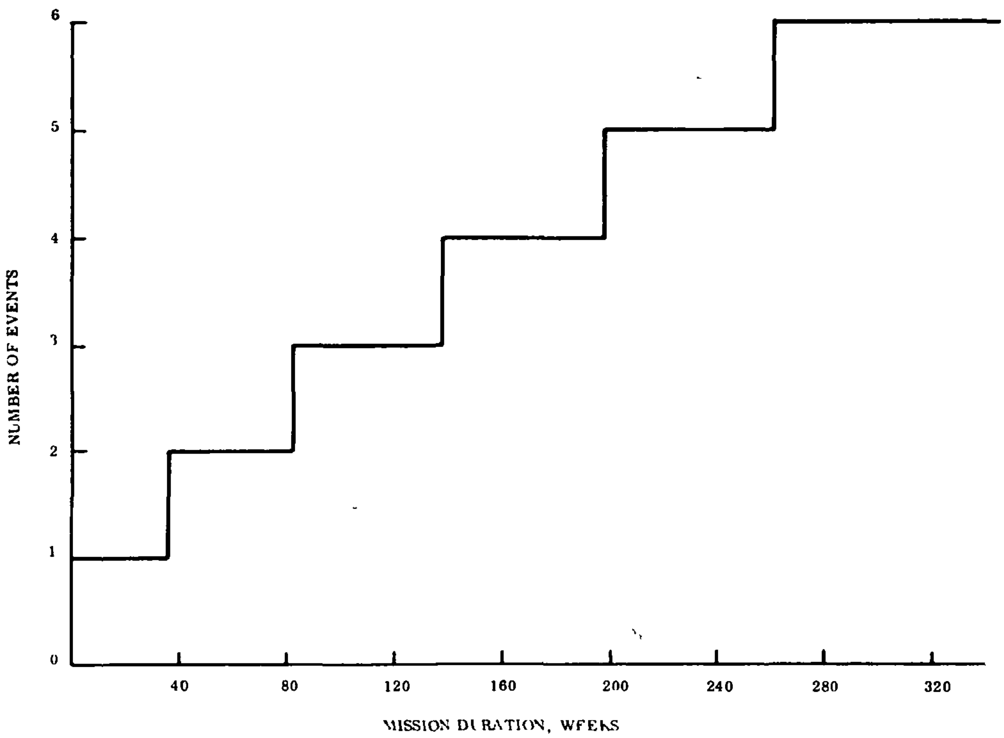


Figure 3-9. Expected Number of Major Solar Particle Events Versus Mission Duration

3.8 1.2 Subsystem Exposure

Table 3-4 shows the environment to which subsystems and equipments would be exposed. The data is presented in units of equivalent 1 Mev neutrons/ cm^2 and rads ionization dose. The neutron dose level given for the natural radiation environment is actually the "equivalent 1 Mev neutron dose", which would cause the same damage as the actual electron, proton and alpha-particle environments encountered. These equivalent doses were developed using the relative damage effects characteristics discussed in Section A.2 of Appendix A.

3.8.1.3 Experiment Exposure

A radiation flux rate above some threshold (a fraction of the experiment signal-to-noise ratio at maximum sensitivity for electronic detectors) causes noticeable dynamic interference (data degradation) in space experiments. Threshold damage was assumed to occur when a signal-to-noise ratio of 10 to 1 was encountered. Doses above some threshold similarly cause permanent damage, however, the threshold for dynamic interference is usually the limiting factor.

Evaluation of dynamic interference in the experiment program due to earth trapped radiation, was based on the flux contours in Reference 3-15 (See Section 6.3.1.4). Table 3-5 shows the particle fluxes associated with the solar flare events and galactic cosmic radiation.

3.8.1.4 Alternate Orbit Inclination Effects

The alternate 30 degree inclination orbit will present a somewhat different radiation environment due primarily to the characteristics of the earth magnetic field encountered at this inclination. In relation to the 55 degree inclination orbit, the trapped proton component will decrease by as much as 50 percent while the trapped electron component will increase. Also the galactic cosmic radiation component will be reduced to approximately 1/3 of the 55 degree inclination dose rate (Reference 3-14).

Of major significance, however, is the fact that for the orbit altitude considered (500 km), the solar flare environment is essentially negligible at the 30 degree inclination because of the shielding provided by the geomagentic field (Reference 3-14).

Table 3-4. Equivalent 1 Mev Neutron and Ionization Doses from Natural Radiation Environments

Radiation Dose Equivalent	Radiation Dose	
	1 g/cm^2 Shielding	10 g/cm^2 Shielding
Equivalent 1 Mev Neutrons/cm^2		
Geomagnetically Trapped	7×10^9/year	2×10^9/year
Solar Flare Events	4.2×10^{10}/10 years (4.2×10^9/year)	5.4×10^8/10 years (5.4×10^7/year)
Rads, Ionization		
Geomagnetically Trapped	4.8×10^2/year	4.8×10^1/year
Solar Flare Events	7.68×10^2/10 years (7.68×10^1/year)	4.8×10^1/10 years (4.8/year)
Galactic Cosmic Ray	3/year	3/year

Note: 472 km (255 nm) 55° inclination circular orbit

Table 3-5. Particle Flux From Galactic Cosmic Radiation and Solar Particle Events

Radiation Source	Particle Flux
Galactic Cosmic Radiation	2.5 - 5 particles/ cm^2-sec with energy >100 Mev
Peak Solar Particle Event	2 x 10^4 protons/ cm^2-sec with energy > 30 Mev

Note:

472 km (255 nm) 55° inclination circular orbit (Reference 3-13)

3.8.2 SPACE BASE REACTOR POWER MODULE RADIATION ENVIRONMENT

The reactor power modules represent a source of gamma photon raditaion when shut down (or prior to full power operation) due to accumulated fission product inventory and activation of the NaK coolant in the primary loop (Section 3.2.2 1). During operation, the reactors are primarily sources of both gamma photons and neutrons due to the fission process, as well as gamma photons from the activated NaK coolant. The reactor is surrounded by a shield to attenuate the radiation.

3.8.2.1 Reactor/ Shield Configuration

Figure 3-10 shows the shaped 4π reactor shield configuration generated by Oak Ridge National Laboratory (Reference 3-16) in accordance with the shielding requirements (References 3-1 and 3-2). The neutron shield consists of a maximum of 79 cm of lithium hydride at the forward portion of the shield (α = 0°) tapering to 56 cm at the rear of the shild (α = 180°). The gamma shielding consists of a maximum of 16 cm of tungsten at α = 0° tapering to 8.5 cm at α = 180°. As shown in Figure 3-10, the Lithium Hydride and Tungsten are arranged in alternate layers.

3.8.2.2 Radiation Environment at Operating Power Levels

The dose rate distribution around each reactor is shown in Figure 3-11 (Reference 3-17) for normal operation at 330 kWt.

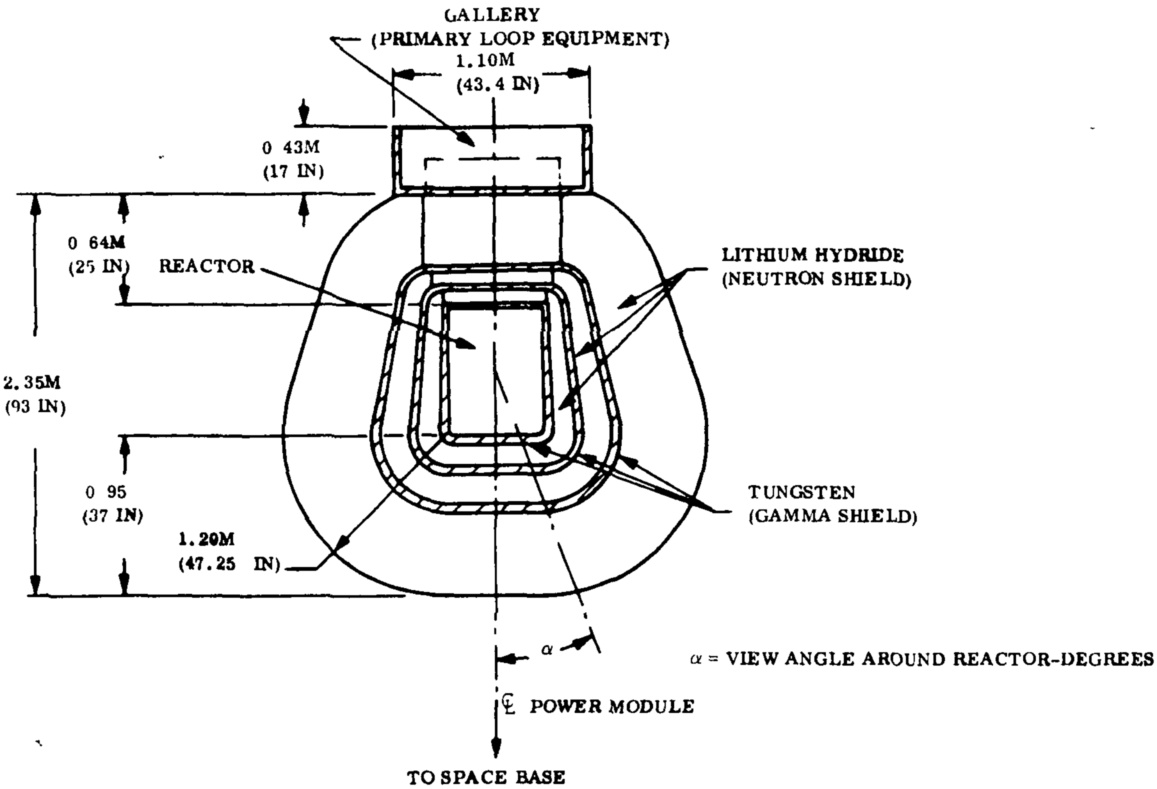


Figure 3-10. Reactor - Shield Configuration

It should be noted that the dose rates from this reactor shield configuration are considerably less than from other manned space reactor shield configurations such as the Space Station shield (Reference 3-18) especially at view angles greater than 30 degrees. (For example, the dose rate at 90 degrees is approximately 1/1000 the dose from the Space Station reactor shield configuration.) Scattered radiation from the power module radiator and the adjacent power module is negligible when employing a shield (Figure 3-10) of the Space Base configuration as shown in Figure 3-3.

3.8.2.2.1 Biological Exposure

Figure 3-12 shows isodose plots in the vicinity of the Space Base for the condition where both reactors are operating at the nominal 330 kWt power level. The dose rate over the habitable area of the base ranges from 0 3 to 1.0 mrem/hour. The dose rate, both internal and external to the Space Base is essentially equal since the vehicle structure provides negligible shielding for gamma rays and neutrons.

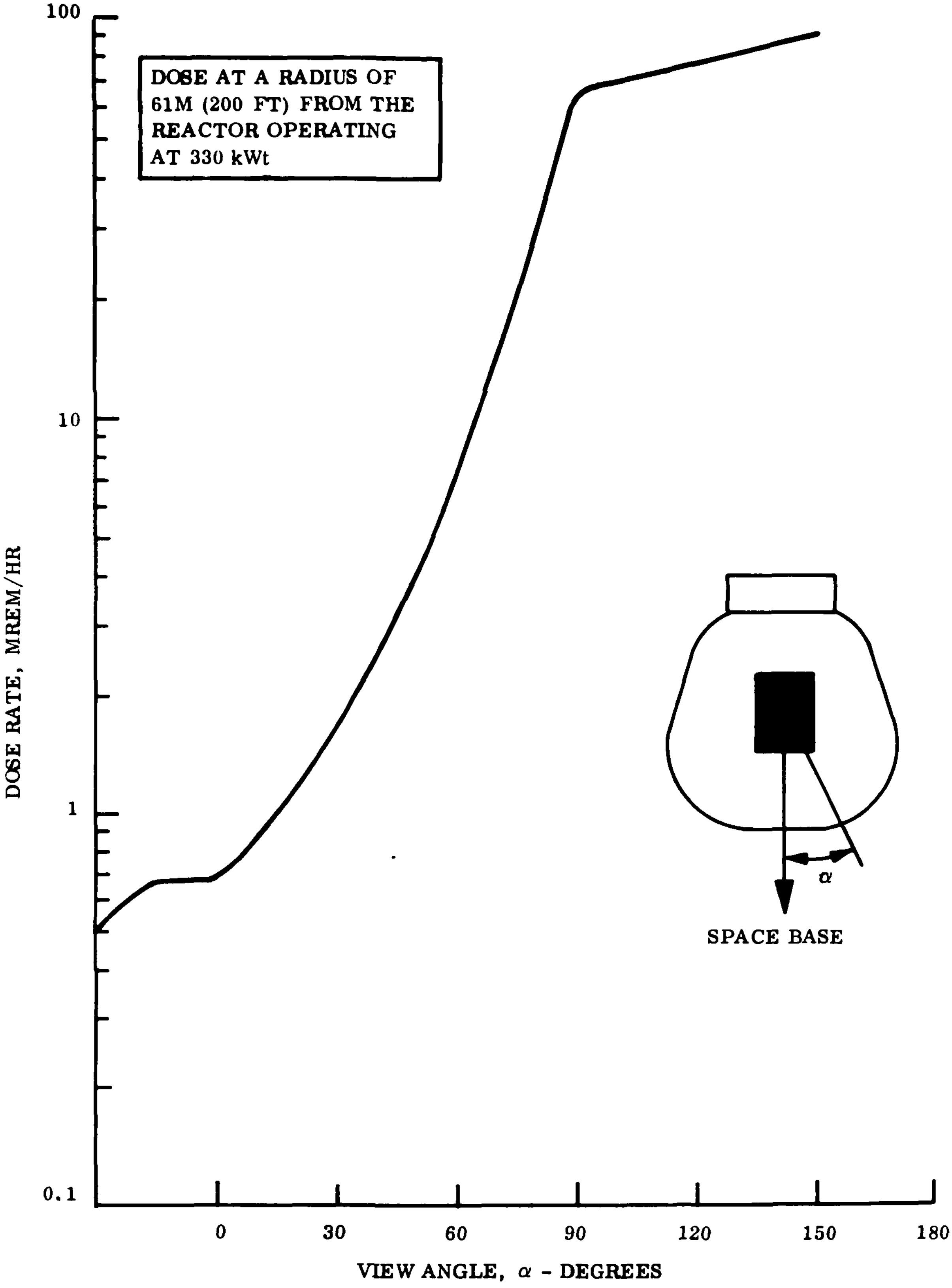


Figure 3-11. Dose Rate as a Function of View Angle

3.8.2.2.2 Subsystem Exposure

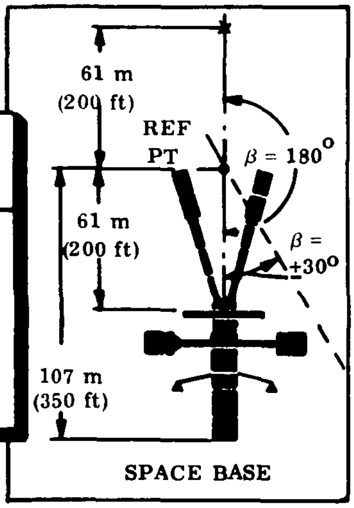
Table 3-6 shows the equivalent environments due to both reactors to which Space Base Program subsystems and equipments will be exposed. (See Section 4.0 and Appendix A.) The positions at the outer line of the Base core modules with $\beta = \pm 30°$ cover the habitable portion of the Space Base vehicle Doses within the $\pm 30°$ subtended angle at a specified distance from the reference point are equal. The doses at $\beta = 180°$ include the contribution from the activated coolant in the primary loop gallery. (See Figure 3-10.)

3.8.2.2.3 Experiment Exposure

Figures 3-13 and 3-14 indicate the shielded reactor flux spectra while operating at 330 kWt. (Reference 3-19). Experiment sensitivity is dependent on quantity and energy levels of the radiation emitted. Figure 3-13 shows the flux spectra within the subtended $\pm 30°$ angle whereas the flux spectra 61m (200 ft) away from the reactor power module and 180° from the Space Base centerline is shown in Figure 3-14. The latter figure includes the contribution from the reactor as well as the activated NaK coolant in the gallery primary loop.

Table 3-6. Equivalent 1 Mev Neutron and Ionization Doses from Space Base Reactor Power Modules

Position	Equivalent 1 Mev Neutron Dose 1 Mev n/cm²-Year	Ionization Dose Rads/year
$\beta = \pm 30°$		
at 61 m (200 ft)	10^8	8
at 107 m (350 ft)	3×10^7	2.5
$\beta = 180°$, 61 m (200 ft)	3.5×10^9	1.5×10^3



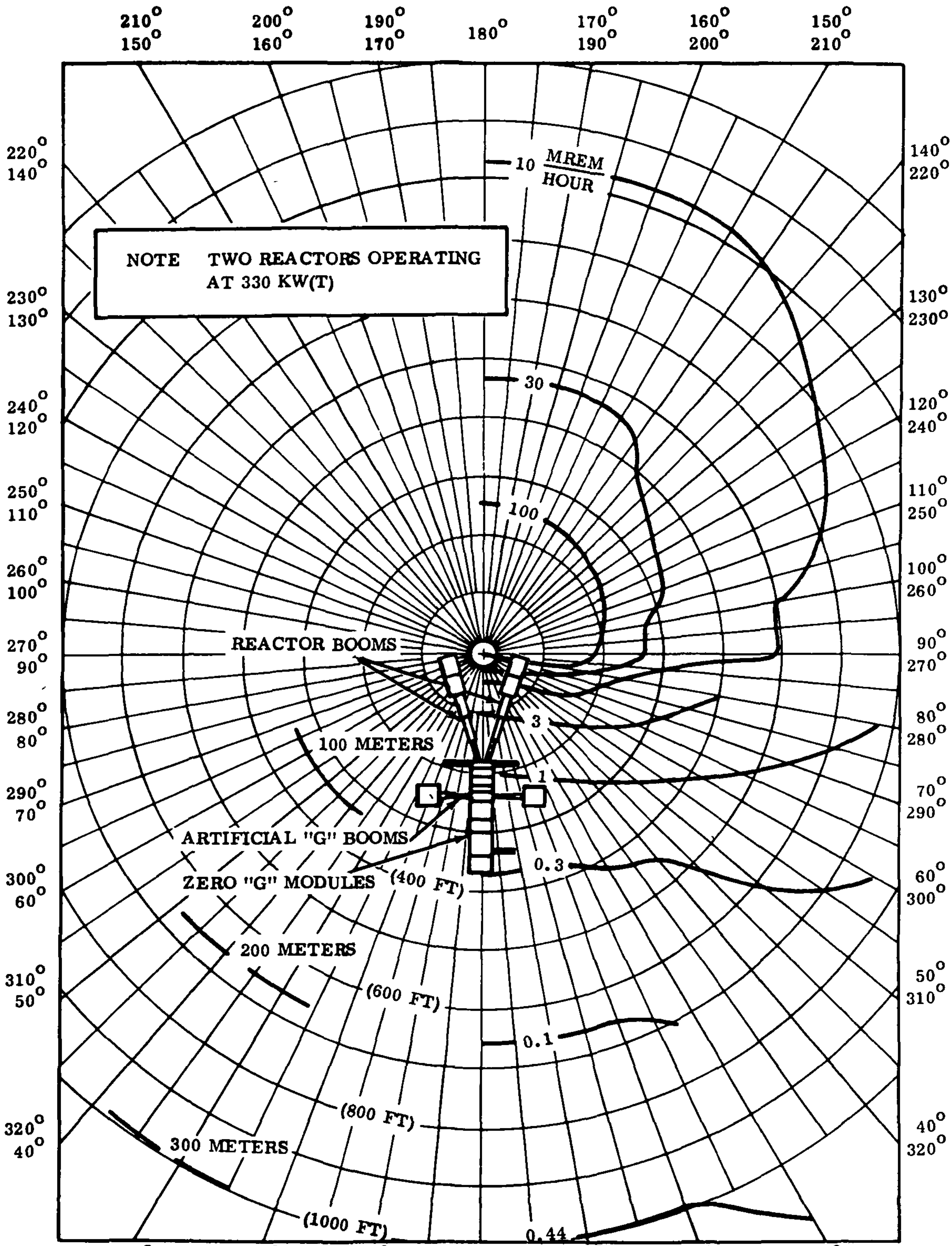


Figure 3-12. Dose Rates in the Vicinity of the Space Base Due to the Reactor Power Modules

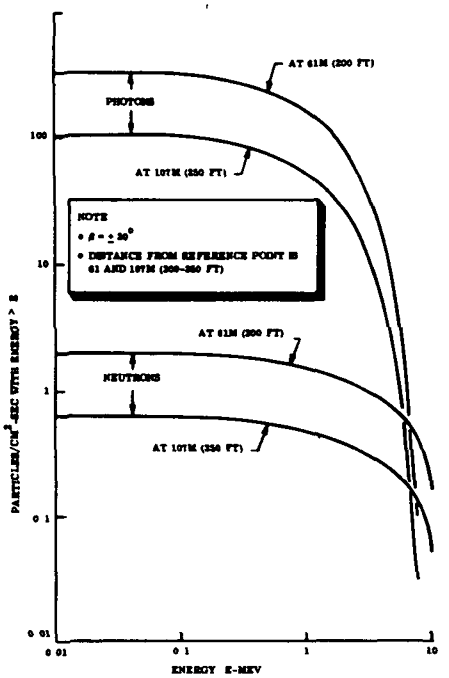


Figure 3-13. Gamma Photon and Neutron Flux Spectra at the Space Base from the Reactor Power Modules

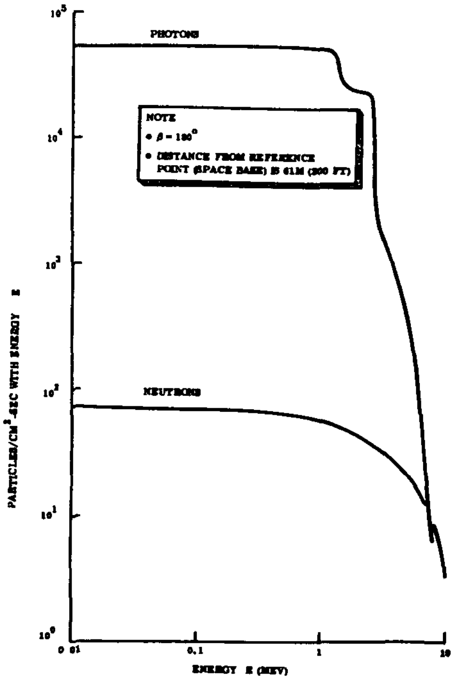


Figure 3-14. Gamma Photon and Neutron Flux Spectra @ $\beta = 180°$, 61m (200 ft) from the Space Base

3.8.2.3 Radiation Environment for Preoperation and Accident Modes

3.8.2.3.1 Preoperation

A ZrH thermal reactor presents a negligible fission product inventory prior to testing and operation. The assumption was made that preoperation low power criticality tests will be limited to 100 watt operation for a maximum of 12 days (~ 30 kW/ hour). Based on this mode of operation, Table 3-7 shows the gamma dose rates immediately after shutdown. Actual dose rates during prelaunch activities (several days after shutdown) would be lower due to the decay of fission products in the core. Figure 3-15 shows the potential fission product inventories and associated body dose that could be released from a damaged reactor as a function of time after low power test.

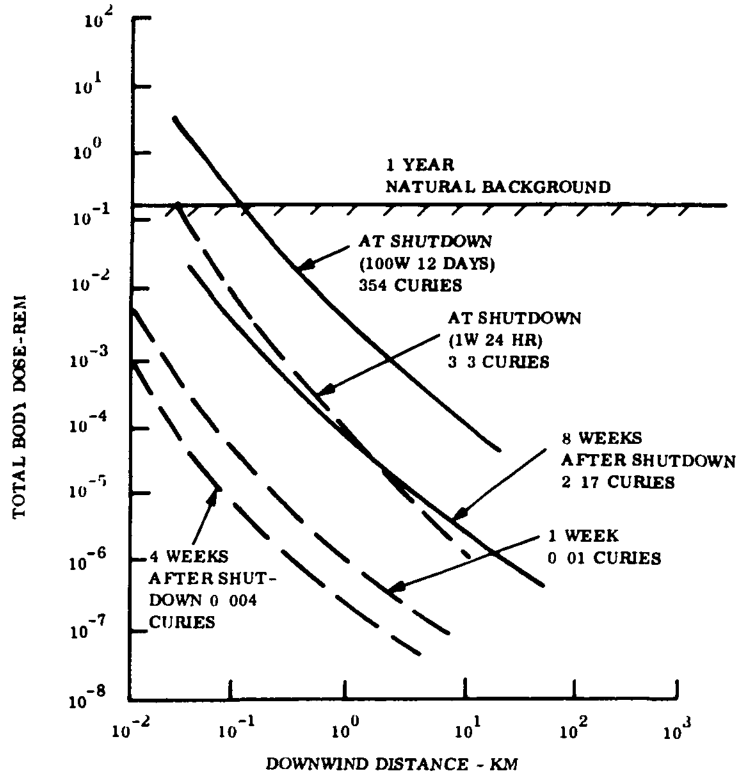


Figure 3-15. Total Body Dose and Fission Products from Damaged Reactor

3.8.2.3.2 Excursion

The radiological characteristics of a reactor excursion are dependent on the fission product inventory within the core and the size of the excursion. Based on ZrH reactor design and SNAPTRAN tests (Reference 3-20) it was assumed that a worst case excursion could produce

an energy equivalent of up to 100 MW-sec. This occurrence is characterized by a prompt gamma and neutron dose and a fission product dispersion. The prompt unshielded dose as a function of distance from the excursion is shown in Figure 3-16. The fission product dispersion from such an excursion is quite limited in area. The envelope of isopleth areas, with radiation levels above the normal yearly background levels of 0.15 rem are confined to within 5 km (3 miles) from the excursion.

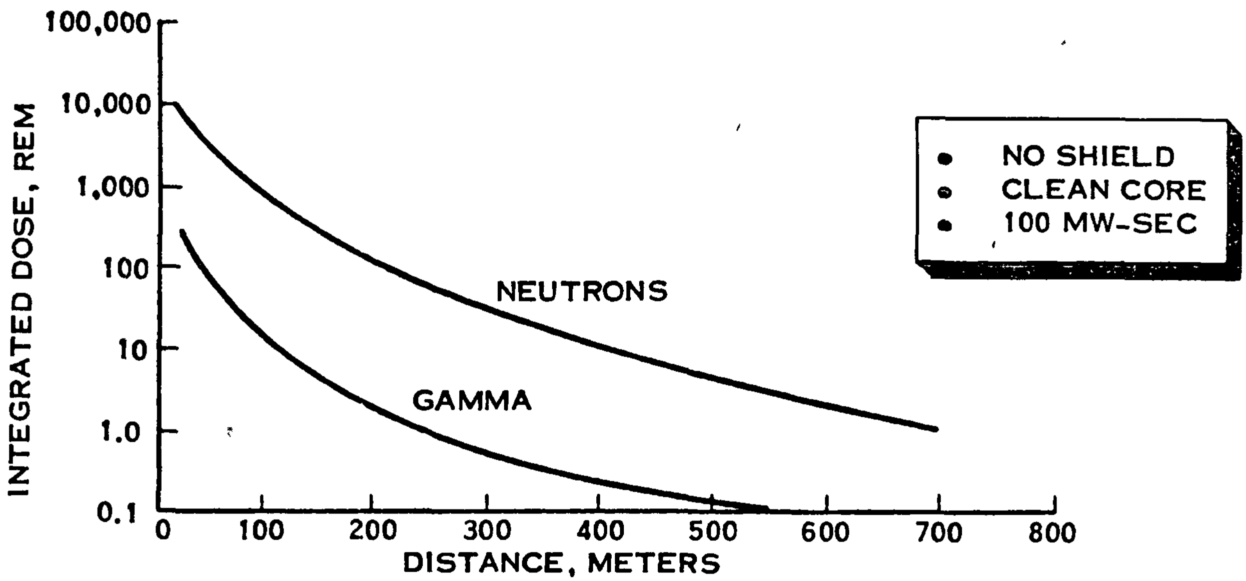


Figure 3-16. Integrated Prompt Dose from Reactor Excursion

3.8.2.3.3 Criticality and Quasi-Steady State Operation

Inadvertent reactor criticality and quasi-steady state operation are also potential hazards. The prime mechanisms which could lead to such events with the ZrH reactor are control drum rotation and/ or core moderation due to the presence or injection of sufficient amounts of hydrogeneous material. In these cases, the radiation levels will be relatively low due to the low power level of the reactor during quasi-steady state operation, and/ or the presence of the shield or equivalent shielding material. The dose rates from a reactor during quasi-steady state operation is shown in Table 3-8.

3.8.3 INTERFACING VEHICLES

Three interfacing vehicles may carry radioactive sources: the Reusable Nuclear Shuttle (RNS), the Orbital Propellant Storage Depot (OPSD), and Detached Experiment Modules (See Section 3.5).

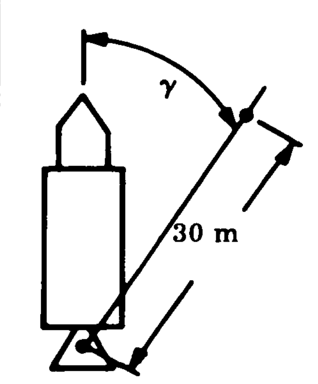
3.8.3.1 Reusable Nuclear Shuttle

The RNS is powered by the NERVA engine which incorporates a nuclear reactor (Reference 3-10). Two operating modes are of interest: (1) The nuclear shuttle thrusting, i.e., the reactor operating, and (2) The engine shutdown after thrusting.

Figure 3-17 shows the biological exposure dose rate at a separation distance of 30 m from an operating (thrusting) RNS at a nominal power level of 1575 MWt. The marked decrease in dose rate as the view angle approaches zero, reflects the shielding on-board the RNS provided for the crew and payload. The dose rate from the shutdown RNS as a function of time after shutdown is shown in Figure 3-18. The effect of view angle on the dose rate is presented in Figure 3-19.

Table 3-9 shows the operating RNS particle fluxes used to evaluate subsystem degradation and experiment dynamic interference. The flux data for a shutdown RNS reactor as a function of time after shutdown, is shown in Figure 3-20.

Table 3-9. Particle Fluxes from the RNS at 30m (100 ft) Separation Distance

	View Angle γ	Equivalent 1 Mev cm^2-sec	Neutron Flux n/cm^2-sec >1 Mev	Photon Flux Photon/cm^2-sec >1 Mev
	30^o	1.22×10^{10}	6.2×10^9	6.4×10^{10}
	90^o	1.14×10^{11}	5.9×10^{10}	3.2×10^{11}
	180^o	1.47×10^{11}	7.6×10^{10}	1.5×10^{11}

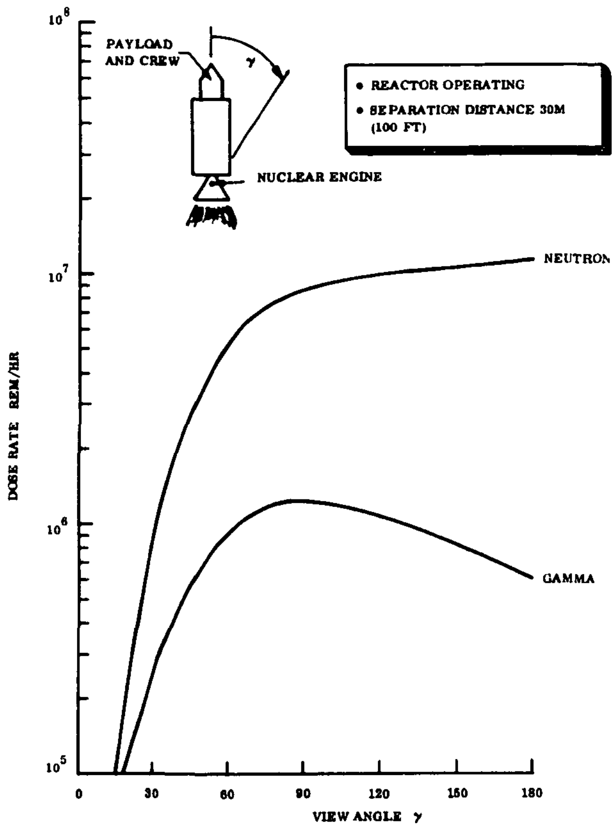


Figure 3-17. RNS Reactor Dose Rate at 30m vs View Angle

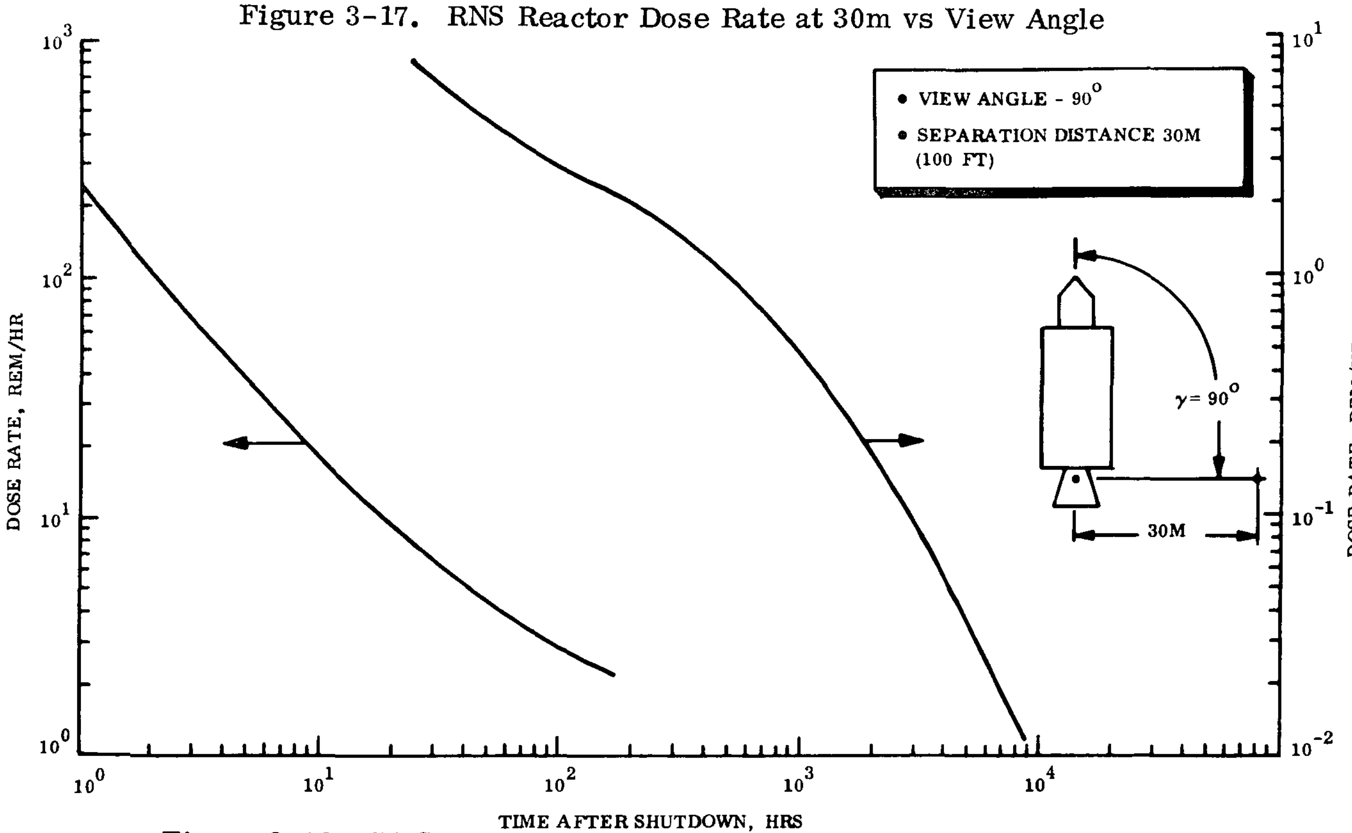


Figure 3-18. RNS Fission Product Dose Rate at 30m as a Function of Time After Shutdown

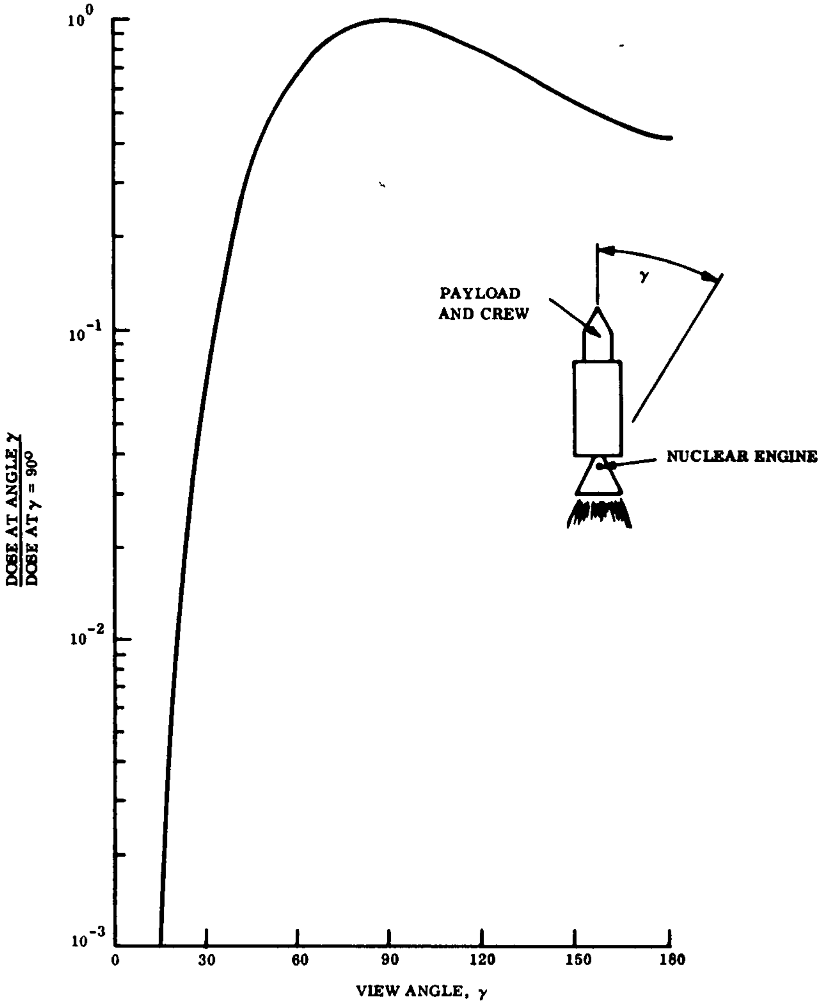


Figure 3-19. Effect of View Angle on Fission Product Dose Rate

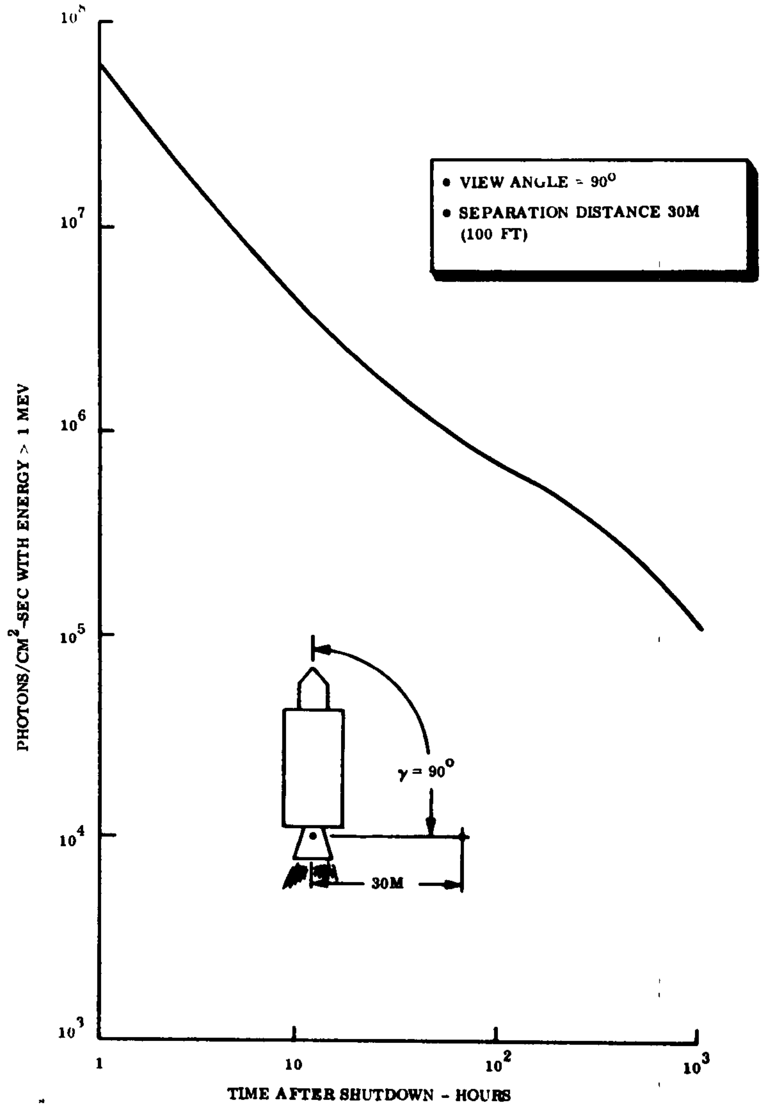


Figure 3-20. Gamma Photo Flux from RNS Fission Products

3.8.3.2 Orbital Propellant Storage Depot (OPSD)

Since the power system for this vehicle is not yet defined, it has been assumed that it employs a Zirconium Hydride thermal reactor with characteristics similar to those employed in the Space Base Power Modules.

3.8.3.3 Detached Experiment Modules

The detached experiment module power requirements range from approximately 2 kWe to as high as 7.5 kWe. The reference power system selected to meet this range of requirements is a solar array/ Ni-Cd battery system (References 3-11 and 3-21).

Consideration has been given to using an array of Radioisotope Thermoelectric Generators (RTG) (Reference 3-22) to supply the lower power levels ~ 2kWe, and an Isotope-Brayton Power System (Reference 3-23) to achieve the higher power levels ~ 7.5 kWe.

3.8.3.3.1 Isotope Heat Sources

Current isotope heat source concepts for experiment module power systems use plutonium-238 or curium-244 in various fuel forms. Heating from these isotopes is due primarily to alpha particle decay and absorption in the fuel and fuel capsule. The radiation field produced by these sources consists of the more penetrating particles, gammas and neutrons. The specific nature of this field is determined by the shielding required by, and incorporated in the actual designs for this application. Table 3-10 identifies characteristics of some of the isotopes which may be used in future heat source applications.

Typical radiation environments associated with several Pu-238 heat sources are shown in Table 3-11. The radiation dose rate as a function of distance from the center of the radiating surface of an unshielded depleted Pu-238 large heat source is shown in Figure 3-21.

3.8.4 EXPERIMENT LABORATORIES

The specific radiological sources associated with the Space Base experiment laboratories are not yet defined. The generic types of equipment may, however, be grouped into three categories: (1) Dynamic generators such as x-ray machines, ion beams, lasers, etc.,

Table 3-10. Characteristics of Radioisotopic Heat Sources

	Co^{60}	Sr^{90}	Ru^{106}	Cs^{137}	Ce^{144}	Pm^{147}	Tm^{170}	Tm^{171}	Tl^{204}	Po^{210}	Th^{228}	U^{232}	Pu^{238}	Am^{241}	Cm^{242}	Cm^{244}
1 Watts/Gram (Pure)[a]	17 4	0 95	33 1	0 42	25 6	0 33	12 1	0 2	0 75	141	170	4 4	0 56	0 11	120	2 65
2 Half-Life, Years	5 3	27 7	1 0	30	0 78	2 6	0 35	1 9	3 8	0 38	1 9	74	86	458	0 45	18
3 Estimated Isotopic Purity, %	10	50	3 3[b]	35	18[c]	95	10[d]	90[d]	20[e]	95	95	85	80	90	90	95
4 Compound Form	Metal	$SrTiO_3$	Metal	CsCl	CeO_2	Pm_2O_3[f]	Tm_2O_3	Tm_2O_3	Tl_2O_3	Metal	ThO_2	UO_2	PuO_2	Metal	Cm_2O_3	Cm_2O_3
5 Active Isotope in Compound, %	10	24	3 3	28	15	82	8 8	79	17 7	95	83	75	70	90	82	86
6 Watts/Gram Compound	1 7	0 23	1 1	0 12	3 8	0 27	1 07	0 16	0 13	134	141	3 3	0 39	0 1	98	2 27
7 Density of Compound, g/cm³ actual or 90% TD	8 7	3 7	12 2	3 6	6 6	6 6	8 5	8 5	9 0	9 3	9	10	10	11 7	9	9
8 Power Density, W/cm³ Compound	15 2	0 94	13 4	0 42	25 3	1 8[f]	9 1	1 36	1 20	1210	1270	33	3 9[g]	1 17	882	20 4
9 Volume for 2 kW of Heat, cm³	132	2130	149	4760	79	1120	220	1470	1650	1 65	1 58	61	513	1710	2 27	88
Type of Radiation (Major)	$\gamma\beta$	βx	$\gamma\beta$x	$\beta\gamma$x	$\beta\gamma$x	β	β	β	β	α	$\alpha\gamma$	$\alpha\gamma$	α	α	αn	αn
Shielding Required[i] [MeV significant β or γ]	Heavy (9 5) [1 33γ]	Heavy (6) [2 26β]	Heavy (9) [3 35β]	Heavy (4 6) [1 17β 0 67γ]	Heavy (10 2) [2 98β 2 18γ]	Minor (1) [0 23β]	Moderate (2 5) [0 97β]	Minor (0 3) [0 1β]	Minor (1) [0 77β]	Minor (1) [0 8γ]	Heavy (11 2) [2 6γ]	Heavy (11) [2 6γ]	Minor (0 1) [0 04γ]	Minor (0 7) [0 06γ]	Minor (0 4) [0 04γ]	Moderate (2) [0 04γ]
Biological Hazard, MPC, μCi/cm³	3×10^{-9}	10^{-10}	2×10^{-9}	5×10^{-9}	2×10^{-9}	2×10^{-8}	10^{-8}	4×10^{-8}	9×10^{-9}	7×10^{-11}	2×10^{-12}	9×10^{-12}	7×10^{-13}	2×10^{-12}	4×10^{-11}	3×10^{-12}
Curies/Gram (Pure)	1130	142	3394	87	3180	928	6048	1150	458	4500	4100[j]	114[j]	17	3 25	3320	81
Curies/Watt	65	148	102	207	126	2788	500	5750	610	32	24	26	30	30	28	29
Spontaneous Fission Half-Life, Years	-	-	-	-	-	-	-	-	-	-	-	8×10^{13}	$4\ 9 \times 10^{10}$	$1\ 4 \times 10^{13}$	$7\ 2 \times 10^{6}$	$1\ 4 \times 10^{7}$
Availability in 1980, kW_t[b]	MWs	850	6500	850	10,000	40	-	-	-	-	-	-	>400[k l]	118 kg[h] 174[l]	-	29[h] 110[l]

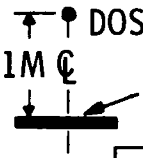
(a) Includes contributions from daughters at equilibrium (thermal watts)
(b) From power reactor fuels, 20,000 MWd/ton, 1 year after discharge
(c) Isotopic purity is not expected to exceed 3% at time of recovery from power reactor fuels
(d) Tm^{170} at this concentration is expected on Tm^{169} irradiation without need for isotopic separation
Tm^{171} requires production from isotopically separated Er^{170} or irradiation of Tm^{169} at very high flux
(e) Tl^{204} at this concentration is probable only with isotopic separation or irradiation at very high flux
(f) Metal may be preferred, m p = 1080°C [F Weigel, Angew, Chem 75 451 (1963) and expected power density = 2 3 W/cm³]
(g) Does not include the usual 1 1 void volume allowance for helium pressurization with this and all other securely encapsulated alpha emitters
(h) From spent fuels from civilian power reactors (95,000 MW_e in 1980)
(i) Except for shielding against neutrons Number in parentheses indicates approximate inches of lead shielding required for 1 kW source for 10 mR/hr at 1 m - (See ORNL-3576 except for promethium and americium)
(j) Alpha disintegration curies including daughters at equilibrium
(k) From accumulated Np^{237} from spent fuels from civilian power reactors (920 kg neptunium recoverable in 1980)
(l) With recycle of plutonium and americium

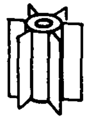
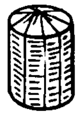
α Alpha
β Beta
γ Gamma
n Neutron
x Penetrating bremsstrahlung

Adapted from Table VI, page 52, HW-76323, Rev 1, "Radioisotopic Heat Sources," 10/15/63, C A Rohrmann Battelle-Northwest Richland, Washington

Table 3-11. Typical Isotope Heat Source Hazards

RADIATION



SYSTEM	FUEL QUANTITY	FUEL TYPE	MAXIMUM DOSE RATE - 1 METER FROM CENTER OF UNSHIELDED SOURCE (MREM/HR) NEUTRON	GAMMA	TOTAL
 SNAP 27 RTG	1500 Wt	$^{238}PuO_2$	92	8	100 (MEASURED)
 MULTI-HUNDRED WATT RTG	2400 Wt	$^{238}PuO_2$	138	12	150 (CALCULATED)
 ISOTOPE BRAYTON HEAT SOURCE	53 kWt	$^{238}PuO_2$	1400	230	1630 (CALCULATED)
 ISOTOPE BRAYTON HEAT SOURCE	53 kWt	$^{238}PuO_2$*	280	230	510 (CALCULATED)

*O^{17}, O^{18} DEPLETION REDUCES NEUTRON GENERATION (EXPECTED FUEL FOR ISOTOPE BRAYTON HEAT SOURCE)

CONSTANT RADIATION AND THERMAL EMISSION

THERMAL

- CONSTANT PRODUCTION OF HEAT - ($Pu^{238} \sim 3.9\ W/CM^3$) ($CM^{244} \sim 21 W/CM^3$)
- HANDLING HAZARD --- 450°K TO 1500°K
- IGNITION SOURCE

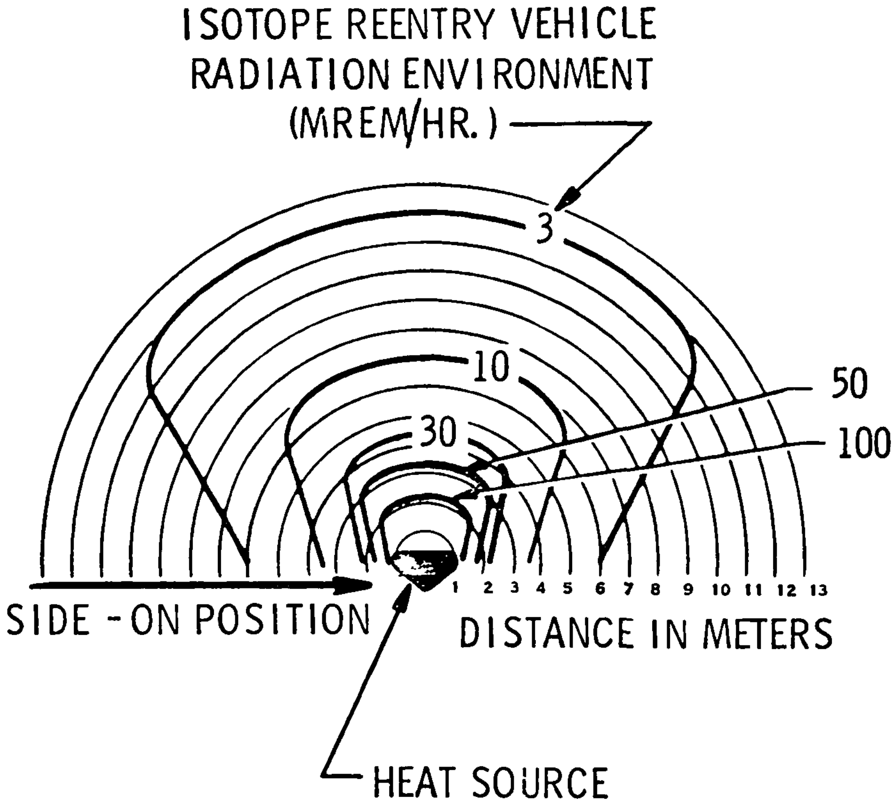


Figure 3-21. Isotope Reentry Vehicle Radiation Environment (mrem/hour)

(2) Open isotope sources such as isotope tracers which could be used in the laboratories without intrinsic containment, (3) Closed sources such as isotope capsules, used as particle sources, heaters, etc., where the source is used in its own container.

Since the location, quantity, and type of these equipments are undefined in the Space Base documentation (References 3-1 and 3-2) and also in the reference experiment program definition (References 3-5 and 3-6) these radiological sources are treated in a qualitative manner with respect to generic types of equipment. Section 7-3 treats considerations in the handling and operation of these sources.

3.9 REFERENCES

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3-3 "Preliminary Safety Analyses Report - Separately Launched Multi-Use Space Electrical Power System"; Volume I, II, III - GE SP-7057; General Electric Co.; August 1970.

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3-12 "Apollo/ Saturn V Facility Description"; NASA KSC Document No. K-V-012; Volume II (of IV Volumes) Launch Complex 39 Facility Description; October 1966.

3-13 Weidner, D. K.; "Natural Environment Criteria for the NASA Space Station Program - Second Edition"; NASA TM X-53865; MSFC; August 1970.

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3-17 Mynatt, F. R., Oak Ridge National Laboratory; Private Communication to J. Loffreda, General Electric Company; November 17, 1971.

3-18 "Nuclear Reactor-Powered Space Station Definition and Preliminary Design"; SD 70-168-3 under contract NAS 9-9953; North American Rockwell, January 1971.

3-19 Mynatt, F. R., Oak Ridge National Laboratory; Personal Communication to J. Loffreda, General Electric Company; November 17, 1970.

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3-22 "Multi-Hundred Watt Radioisotope Thermoelectric Generator Program - Phase I Final Report"; USAEC Document No. GEMS-403 (GESP-7055) under contract AT-29-2-2831; General Electric Company; July 1970.

3-23 "Study of a Separately Launched Multi-Use Space Electrical Power System"; GESP-7007-2; General Electric Company, Space Division; November 1968.

SECTION 4
NUCLEAR RADIATION EXPOSURE LIMITS SUMMARY

KEY CONTRIBUTORS

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SECTION 4
NUCLEAR RADIATION EXPOSURE LIMITS SUMMARY

4.1 GENERAL

In order to analyze and evaluate the effect of radiation on the Space Base program, a reference set of exposure limits has been compiled. These limits indicate:

- Exposure established and recommended for crew, radiation workers and general populace.
- Subsystem and equipment damage tresholds.
- Experiment degradation (dynamic interference) thresholds.

In compiling the exposure limits, effects of the various radiations from the nuclear sources described in Section 3.8 were considered. The limits are based on a broad literature search and a comprehensive investigation of the types of materials, equipments and detectors likely to be associated with a Space Base program. Appendix A contains the detailed nuclear radiation exposure limits data and discussion including reference sources of data and a discussion of relative effects. The following sections summarize the key exposure limits used in the hazard evaluations of Sections 5 and 6.

4.2 PERSONNEL EXPOSURE LIMITS

The radiation exposure limits for personnel associated with the Space Base program have been grouped according to those making up the flight crew of the Space Base and those involved in ground support operation Exposure limit criteria for the general populace can be found in Section 5 of this Volume and in Volume III of this report.

4.2.1 SPACE BASE CREW

Table 4-1 shows the Radiation Exposure Limits for manned space flight (Reference 4-1 and 4-2). These data are based on Reference 4-3 which was subsequently amended to eliminate the testes reference dose as a primary design criteria. The dose and dose rate limits apply to all sources of exposure and therefore apply to natural as well as man-made sources of radiation.

Table 4-1. Radiation Exposure Limits for Manned Space Flight

Reference 4-1, 4-2

Constraints in rem	Bone (5 cm)	Skin (0.1 mm)	Eye (3 mm)	Testes[2] (3 cm)
1 yr. avg. daily rate	0.2	0.6	0.3	0.1
30 day max.	25	75	37	13
Quarterly max.[1]	35	105	52	18
Yearly max.	75	225	112	38
Career limit	400	1200	600	200

1. May be allowed for two consecutive quarters followed by six months of restriction from further exposure to maintain yearly limit.

2. These dose and dose rate limits are applicable only where the possibility of oligospermia and temporary infertility are to be avoided. For most manned space flights, the allowable exposure accumulation to the Germinal Epithelium (3 cm) will be the subject of a risk/gain decision for the particular program, mission, and individuals concerned.

Further discussion of radiobiological dose considerations on humans can be found in Appendix A, Section A.5.

4.2.2 GROUND SUPPORT PERSONNEL

Table 4-2 indicates the dose limits for ground radiation workers. This data is based on recommendations by the Federal Radiation Council and the National Committee for Radiation Protection (Reference 4-4 and 4-5). Additional detail on permissible concentrations of various radionuclides is given in Appendix A, Section A.5.

4.3 SUBSYSTEMS AND EQUIPMENT

The sensitivity of Space Base subsystems to the radiation environment can be discussed in terms of effects on electronic components and effects on other spacecraft material. The effects on semiconductor electronics may be described in relation to two mechanisms: bulk damage effect which is the disruption of the crystal lattice, and ionization effects which result from interactions of ionized gases with ionized semiconductor surface impurities. Other

subsystem materials respond in different manners to radiation environments ranging from loss of flexibility and outgassing in plastics to very insensitive materials to ionization such as dry lubricants.

Three levels of damage have been defined as follows:

- Threshold damage--Specific effects occur which would likely require consideration in design to insure proper operation.
- Moderate damage--Significant degradation of component performance occurs requiring special design considerations.
- Severe damage--Operation seriously impaired, possibly requiring new design approaches and/or use of different materials.

Table 4-2. Dose Limits for Ground Radiation Workers.

Currently in Use (10 CFR 20) Reference 4-4

Exposure	Condition	Dose (rem)
• WHOLE BODY - Head, trunk, active blood forming organs, gonads, lens of eye	Accumulated Quarterly	5(N-18 yr) 1.25
• SKIN - of whole body	Year Quarterly	30.00 7.50
• HANDS - and forearms, feet and ankles	Year Quarterly	75.00 18.75

Recommended (NCRP-39) Jan. 15, 1971 Reference 4-5

Exposure	Condition	Dose (rem)
• WHOLE BODY	Long Term Accumulated	5(N-18 yr) 5/year
• SKIN	Year	15
• HANDS, FEET & ANKLES	Year Quarterly	75 25
• FOREARMS	Year Quarterly	30 10
• OTHER ORGANS	Year Quarterly	15 5

Figure 4-1 and 4-2 show the subsystem and equipment damage thresholds for bulk damage effects (normalized to equivalent 1 MeV neutron effects--see Appendix A, Section A. 2) and ionization effects, respectively. The damage levels are based on the total integrated dose received. In general, radiation dose rate effects are not considered to be of significance for the anticipated radiation environments; an exception being the use of star trackers for navigation and control. The threshold dose rate for such startrackers could be approximately one (1) to 1000 rad/hr depending on the particular detector characteristics. Other components would exhibit a tolerance to greater than a megarad/hr dose rate.

Section A. 2 of Appendix A specifies component sensitivity and comments on availability of data and susceptibility to bulk effects or ionization effects.

4.4 EXPERIMENT EXPOSURE LIMITS

Experiments will use electronic and other equipment similar to that used to implement the Space Base subsystems. Therefore, the exposure limits discussed in Section 4. 2 would apply in evaluating their susceptibility to bulk damage and ionizing radiation. However, two other types of radiation exposure must be considered for the experiment program. These are (1) limits to the exposure of bioscience experiments and (2) data degradation (dynamic interference) due to "noise" generated by radiation effects in particle sensitive equipment, i. e., experiment interference.

4.4.1 BIOSCIENCE EXPERIMENTS

In most cases organisms associated with the Space Base experiment program (see Section 3. 3) are more resistant to radiation than man. This is particularly true of the invertebrates. However, the stage of genetic development may have a pronounced effect on the sensitivity of animals and plants to radiation. An example of an organism which exhibits a wide range of resistance is the fruit fly. The adult fly has an LD_{50-1} (dose required to kill 50 percent in one day) of 60 to 200 kilorads depending on age. The LD_{50} of fruit fly eggs is less than 200 rads.

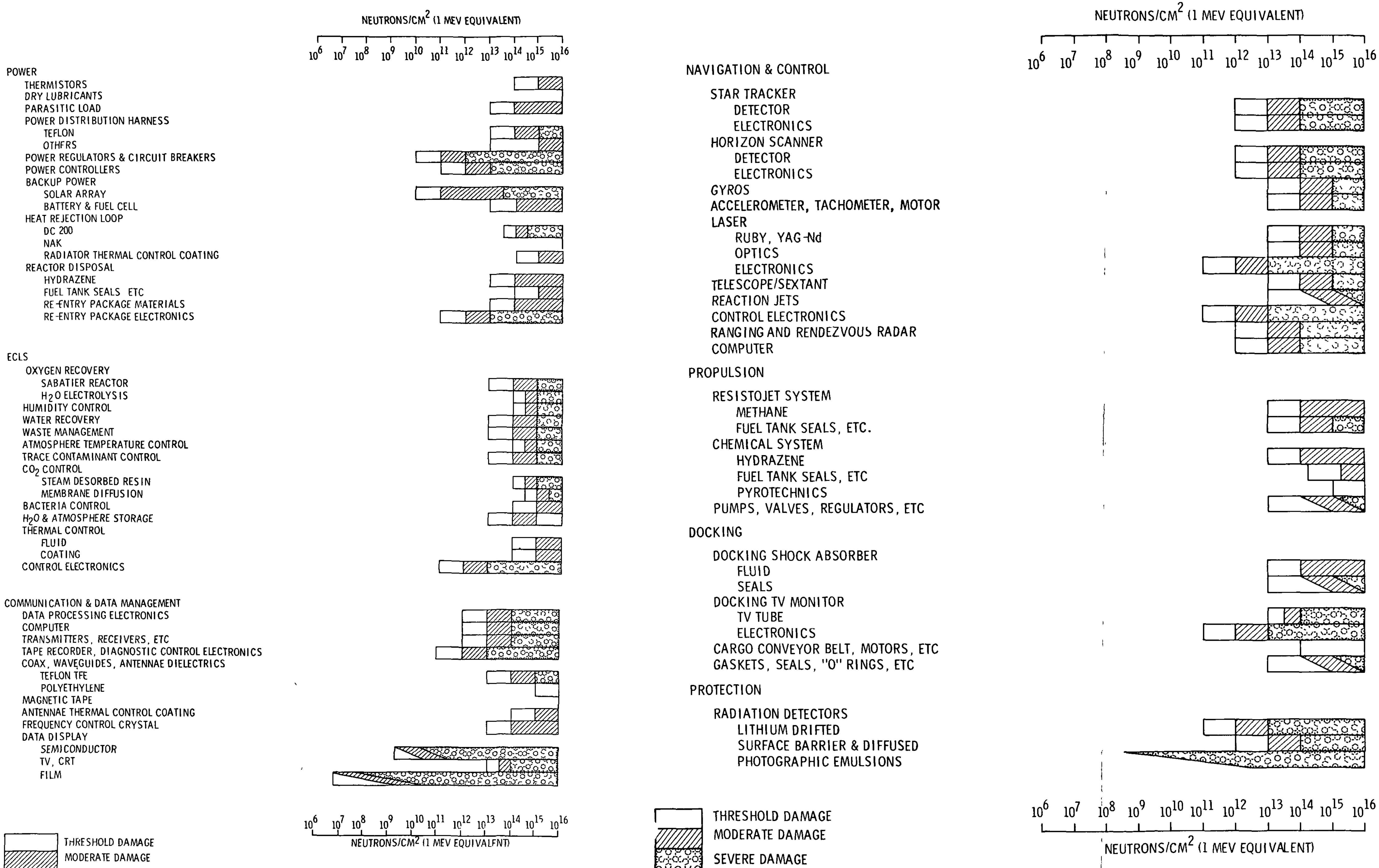
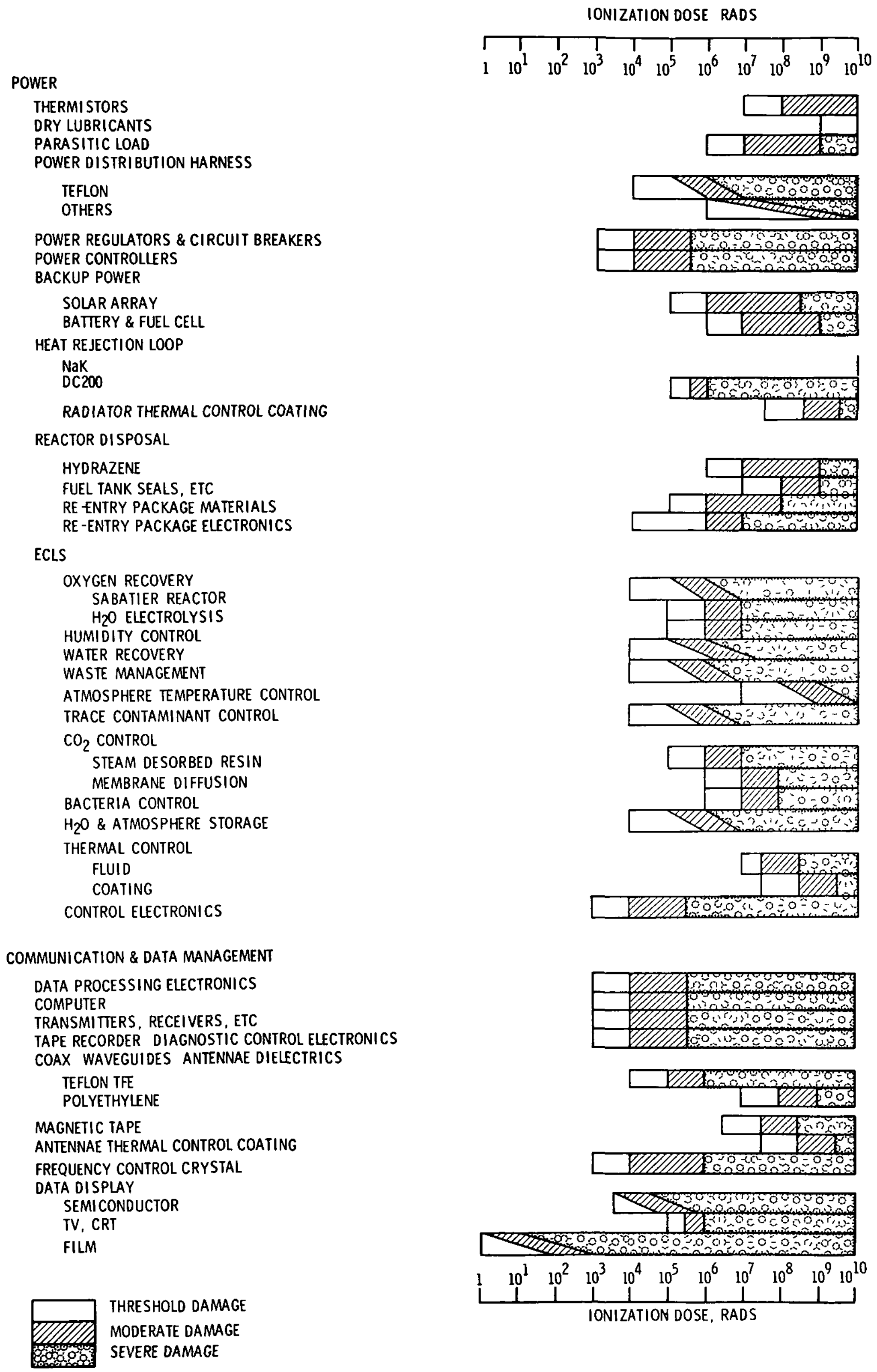


Figure 4-1. 1 MEV Neutron Effects, Space Base Support Subsystem Components



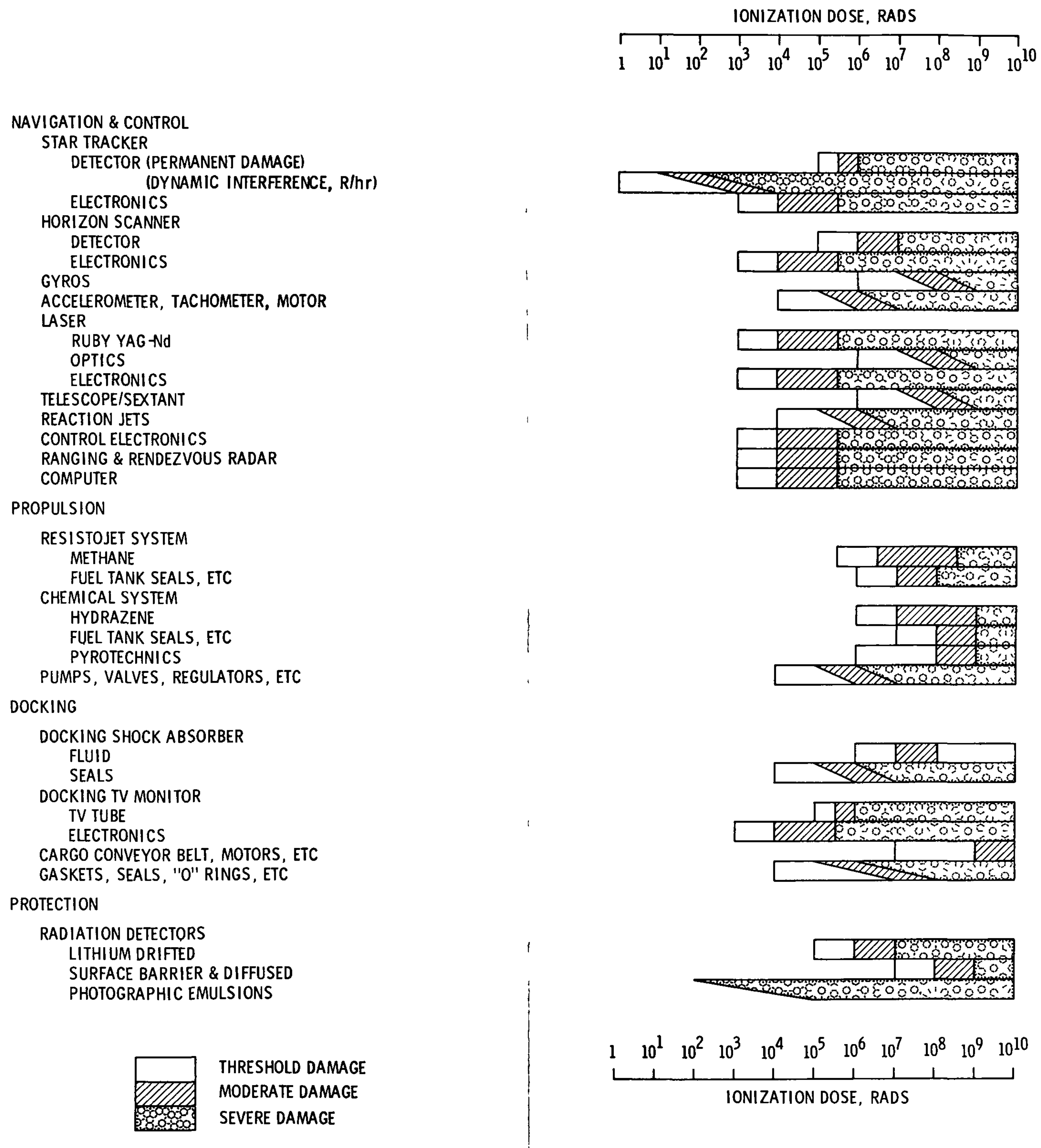


Figure 4-2. Ionization Effects, Space Base Support Subsystem Components

Figure 4-3 illustrates the wide range of experiment sensitivity for specimens which may be associated with the Space Base experiment program. As can be seen, the experiment objectives and the condition of the specimen are particularly important in assessing sensitivity.

Additional data for specific specimens and biologically important compounds are contained in Section A.4 of Appendix A.

4.4.2 EXPERIMENT DYNAMIC INTERFERENCE

The term interference is explicitly meant to describe a rate-sensitive noise component which degrades the results (data) of the experiment. Examples are airglow photometer saturation (Reference 4-4) in the Van Allen belts and dynamic interference in sensitive gamma ray spectrometers due to the use of on-board nuclear sources.

Figure 4-4 shows an example of the sensitivity of some of the experiments and instruments associated with the astronomy discipline. The threshold particle flux that would cause interference is shown for each of the various particles (protons, p; electrons, e; gamma rays, γ; neutrons, n) which could be encountered. The permanent damage threshold is also indicated. The dynamic interference threshold values indicate the radiation flux that would cause a noise level of 1/10th the maximum signal sensitivity for the experiment.

Selected environments may be superimposed on Figure 4-4 to illustrate an approach to evaluating the sensitivity of the various experiments to the specific particle environment. This technique is applied in Section 6.3.1.4 where a discussion of the specific susceptibility of the experiment program to the natural environment and the Space Base induced environment is presented.

Section A.3 of Appendix A presents a comprehensive discussion of the experiment program sensitivity and details the approach to sensitivity evaluation including important assumptions made.

EXPERIMENT CATEGORY	SPECIMEN	TYPICAL EXPERIMENTS
ANIMALS	VERTEBRATES	
	CHIMPS	METABOLISM, CARDIOVASCULAR, CNS
	MONKEYS	METABOLISM, BEHAVIOUR, CARDIOVASCULAR, CNS
	RATS	EMBRYOGENESIS, GROWTH, METABOLISM
		BEHAVIOUR, CIRCULATION, BIORHYTHMS
	MICE, HAMSTERS, RABBITS	EMBRYOGENESIS, GROWTH, METABOLISM
	MARMOTS	IMMUNE RESPONSE
	FROGS	EMBRYO AND DEVELOPMENT
	TURTLES	GROWTH AND METABOLISM
	INVERTEBRATES	
-	FRUIT FLY	LIFE CYCLE, GENETICS
		METABOLISM, BIORHYTHMS
	HOUSE FLY	AGING
	FLOUR BEETLE	MOIPHOGENESIS
	BEES AND SPIDERS	BEHAVIOUR
PLANTS	WHEAT	GROWTH
		METABOLISM AUXIN
	PEA	GROWTH
	ARABADOPSIS	DEVELOPMENT
	P. LONGFOLIA	METABOLISM, MORPHOGEN, FERTILIZATION
	CUCUMBER	LIGNIFICATION
	PINTO BEAN	BIORHYTHM
MICROBIOLOGICAL	VERTEBRATES	TISSUE FUNCTION
	AVIAN	EMBRYO DEVELOPMENT
	VIRUS BACTERIA	HOST PARASITE
	FUNGI	BIORHYTHM
	CELL	CELLULAR FUNCTION
		METABOLISM
	GENES	GENETIC STABILIZATION

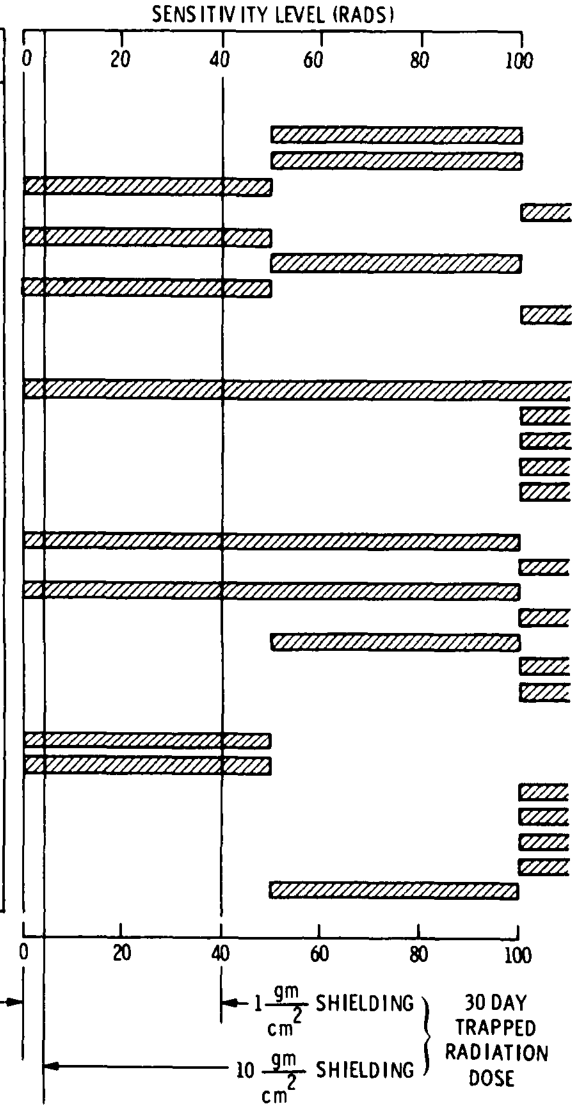


Figure 4-3. Bioscience Experiment Radiation Sensitivity

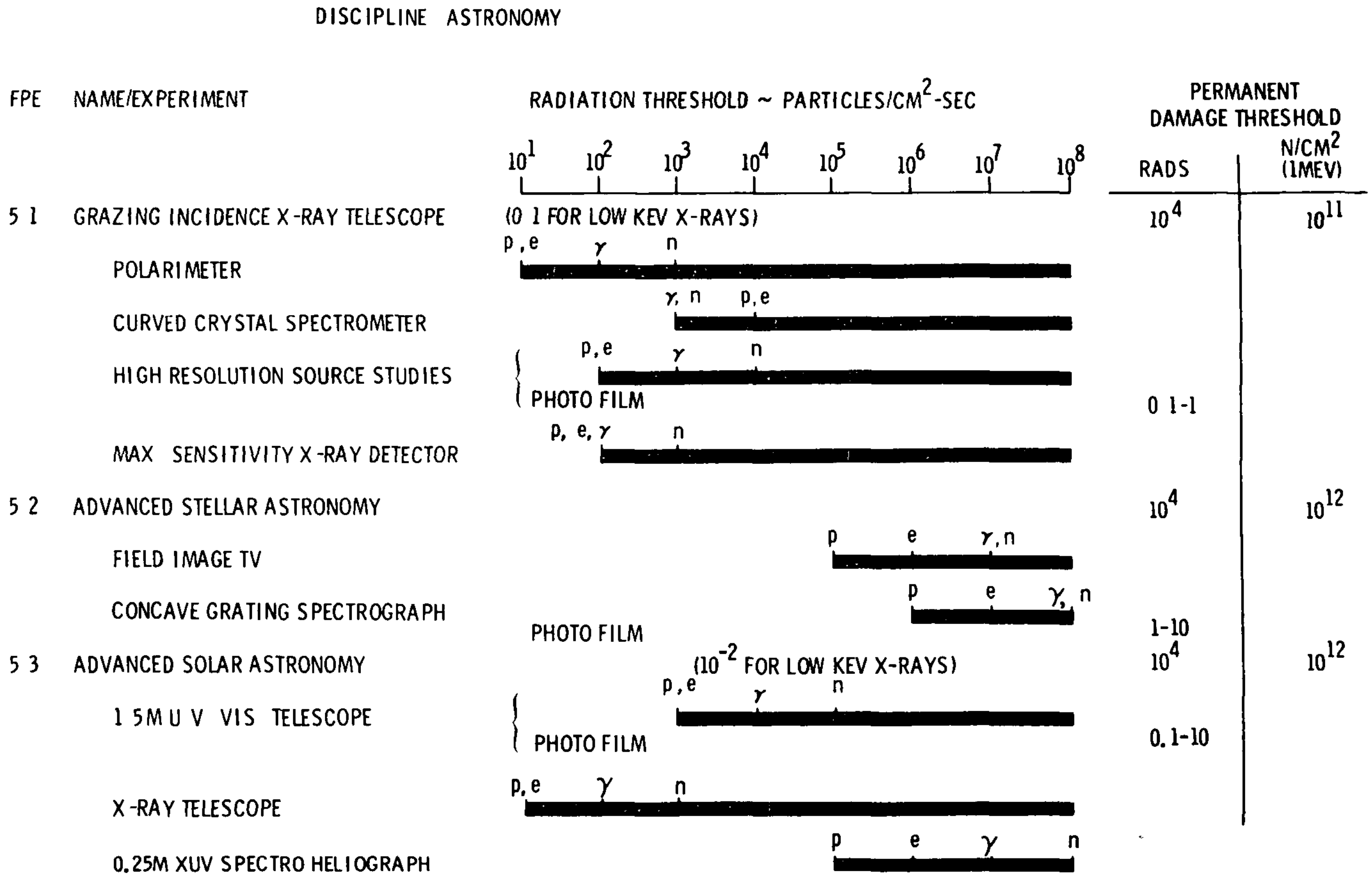


Figure 4-4. Experiment Radiation Sensitivity Thresholds

4.5 REFERENCES

4-1 Berry, C.A. and Rose, R.G.; "Radiation Dose Limits for Manned Space Flight in Skylab, Shuttle, and Space Station/Base Programs"; letter to distribution; January 1971.

4-2 Humphreys, Jr., J.W.; "Radiation Exposure Criteria for Space Vehicle Design Studies"; letter to distribution; March 1971.

4-3 "Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems"; Report of the Radiobiological Advisory Panel of the Committee on Space Medicine, Space Science Board, National Academy of Sciences-National Research Council; 1970.

4-4 "Standards for Protection Against Radiation;" 10CFR-20, Code of Federal Regulations Titles 10-11; January 1968.

4-5 "Basic Radiation Protection Criteria," NCRP Report No. 39; National Council on Radiation Protection and Measurements; January 1971.

SECTION 5

NUCLEAR SAFETY IN MISSION SUPPORT OPERATIONS

KEY CONTRIBUTORS

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SECTION 5
NUCLEAR SAFETY IN MISSION SUPPORT OPERATIONS

5.1 GENERAL

Operations associated with nuclear flight hardware and support equipment of future manned space programs shall be safety implemented to minimize the risk to personnel and the ecology and provide assurance of mission success. Nuclear safety at the launch and flight support facilities can be provided through safety oriented planning and analysis of mission operations followed by implementation of design, operational, and procedural safeguards during the design and development phases of a program.

The largest nuclear hardware launched to date has been the 5 kWe SNAP-10A reactor from the Western Test Range (WTR) and the 0.07 kWe SNAP-27 Radioisotope Thermoelectric Generator employed on recent Apollo flights from the John F. Kennedy Space Center (KSC).

As power requirements and mission durations increase, nuclear reactors of 25-100 kWe may be employed. The 50 kWe ZrH reactors used in this Space Base study are typical of large nuclear powerplants of the future. Additional radiation sources on-board the Space Base include X-ray equipment and small amounts of isotope tracers in the experiment laboratories. Future missions may alsoemploy isotope heat sources for waste management, reaction control and various experiment systems in addition to providing 10 to 25 kW of electrical power.

This section is primarily concerned with the nuclear safety analysis and recommendations to minimize or eliminate potential nuclear hazards associated with supporting operations involved in the Prelaunch, Launch/Ascent and the End of Mission/Recovery Phases of a mission. (Sections 6 and 7 contain the nuclear safety considerations for the orbital phase of the mission.) Most of the supporting operations are performed at KSC. As the mission progresses, the operations are spread to several locations around the world and the Mission Control Center, but are reduced in scope due to the increased role assumed by the crew in the operational phase. It must be recognized that logistic activities such as the replacement

and disposal/recovery of nuclear hardware again necessitate extensive launch center and mission support.

Specific recommendations identified from the analysis of mission support operations form the basis for guidelines and requirements specified in Volume V, Part 1, "Nuclear System Safety Guidelines - Space Base Nuclear Safety".

5.2 PRELAUNCH OPERATIONS SUPPORT

The Prelaunch Phase of the mission provides extensive interfaces of nuclear hardware with supporting personnel, facilities and other flight hardware at the launch complex. The launch complex environment can be substantially different and in some cases more hostile than that provided within a controlled nuclear facility. Adherence to procedures and implementation of safeguards for the protection of flight hardware, facilities and personnel are required to assure a minimum impact on prelaunch operations and schedules.

The Prelaunch Phase starts with the arrival of the hardware at the KSC and terminates with lift-off of the booster from the launch pad. A typical prelaunch ground flow plan is presented in Figure 5-1. It should be noted that the reactor power module is shipped to KSC, complete with the exception of disposal ordnance and rocket motors. The nuclear hardware (power modules) arrive by air, truck, rail or barge and are immediately transported to a Nuclear Assembly Building (NAB) designated for storage and checkout of nuclear hardware. Only air or barge transportation is considered feasible with large power modules (Figure 3-3), due to their size. Receiving inspection, checkout, subsystem and integration tests and storage take place in the NAB. When ready for mating to the launch vehicle or Space Base core modules, the reactor power module is moved from the NAB to the Vehicle AssemblyBuilding (VAB) or the Launch Complex by transporter. After vehicle integration, launch and range checks, and overall acceptance tests are complete, ordnance installation and fuel loading are commenced; culminating in the terminal countdown and liftoff. The cycle just described, exclusive of storage, is anticipated to require about 90 days. Storage of specific nuclear hardware may be at least one year, replacement hardware necessitating the longest shelf life, possibly up to 5 years.

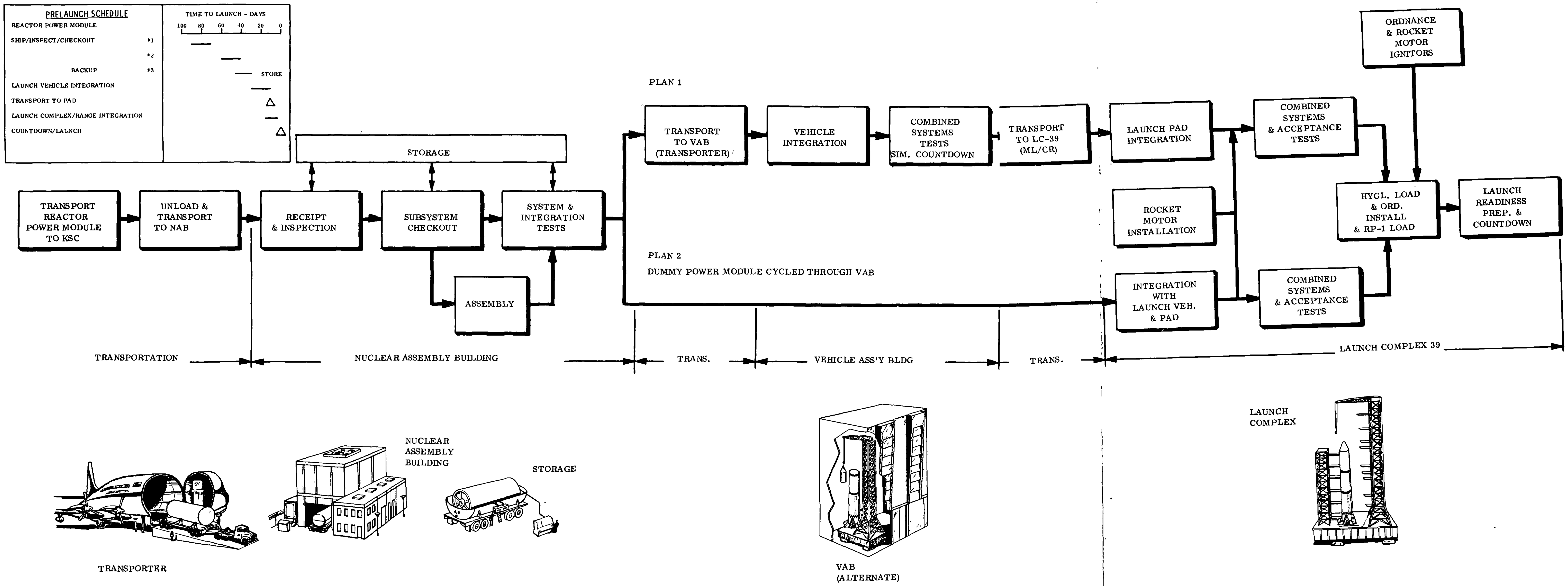


Figure 5-1. Prelaunch Ground Flow Plan (Reactor Power Module)

The principal facility and supporting system interfaces with mission nuclear hardware during prelaunch operations are identified in Table 5-1. The nuclear safety interactions and support involved during prelaunch operations are addressed in the analysis.

5.2.1 RADIATION HAZARDS

5.2.1.1 Isotopes

The principal nuclear radiation hazards during prelaunch emanate from reactor and isotopic sources as defined in Section 3.

The most common hazards associated with the handling of isotopic heat sources are the thermal environment and the nuclear radiation field around the source. Typical radiation environments associated with several Pu-238 heat sources were shown in Table 3-11 Section 3. Adherence to safety regulations and operating procedures combined with proper handling equipment can practically eliminate the risk to personnel and equipment. Potentially serious, but relatively remote prelaunch hazards involved with isotope sources are the release of fuel into the environment and the development of critical masses as a result of prelaunch accidents. Key design features essential in the prevention of these hazards include:

1. Cooling provisions - to lower capsule temperatures to prevent fuel clad ruptures and reduce ignition potential.
2. Packaging for storage - to prevent the assembly of a critical mass.
3. Shielding provisions - to reduce the radiation dose received by ground personnel.
4. Fuel capsule containment - to prevent release of fuel under all possible normal and abort environments, and
5. Fragmentation shielding - to reduce fuel capsule rupture due to explosive accidents.

Table 5-1. Potential Nuclear Hardware Interfaces during Prelaunch Operations

NUCLEAR HARDWARE OPERATIONS / POTENTIAL INTERFACES	Vehicle Assembly Building	Mobile Launcher	Nuclear Assembly Building	Liquid Metal Servicing Facility	Launch Pad	Mobile Service Structure	Launch Vehicle	Range	Launch Control Center	Skid Strip	Barge Canal & Terminal	Banana River	Railroad	Crane	Power Module Transporter	Crawlerway	NASA Causeway	Kennedy Parkway	Banana Creek	Other Nuclear Hardware	Ground & Electrical Support Equipment	Environmental Control Systems	Ordnance Devices	Cryogenics/Propellants	Rocket Motors	Truck	ATMX Railcar (Isotope Brayton)	Simulators	TLM
Transportation										⊗	X	X	○		X		⊗	⊗	⊗			⊗				⊗	○		
Unloading - Loading										⊗	X		○	⊗	X							⊗				⊗	○		
Receipt & Inspection			⊗											X	X						⊗	⊗							
Storage			⊗												X					⊗	⊗	⊗					○		
Prelaunch Checkout & Assembly			⊗	X										⊗						⊗	⊗	⊗							
System Integration Tests			⊗																	⊗	⊗	⊗						⊗	
Launch Vehicle Integration	X	⊗					⊗		⊗					⊗	X					⊗	⊗	⊗				○		⊗	
Combined Systems Tests	X	⊗					⊗	⊗	⊗												⊗	⊗						⊗	⊗
Transport to Launch Pad	X	X	○		⊗		X		X						X	X			X		⊗	⊗				○			
Launch Pad Integration		⊗			⊗	⊗	⊗		⊗					⊗						⊗	⊗	⊗							
Combined Space Vehicle & Range Tests		⊗			⊗		⊗	⊗	⊗											⊗	⊗	⊗						⊗	⊗
Ordnance/Rocket Installation		⊗				⊗	⊗													⊗	⊗	⊗	⊗		⊗				⊗
Countdown		⊗			⊗		⊗	⊗	⊗											⊗	⊗	⊗	⊗	⊗	⊗				⊗
Contingencies		⊗	⊗	X	⊗		⊗		⊗					⊗	X					⊗	⊗	⊗	⊗	⊗	⊗				⊗

X Reactor Power Modules
○ Isotopes
⊗ Both

The advancement of fuel capsule encapsulation and fabrication technology is vitally important to isotope safety since the principal hazards result from the release of inhalable and ingestible fuel in the form of fines of less than 4μ. The development of new and improved fuel forms and refined encapsulation techniques combined with integral reentry materials is currently being pursued by the Atomic EnergyCommission.

5.2.1.2 Reactors

The radiological hazard characteristics of a nuclear reactor can be quite different from those of an isotope heat source (Reference Section 3). The performance of final assembly and low power criticality checks prior to delivery to KSC permit pre-operational checks of a relatively clean reactor in a low radiation environment during prelaunch activities. This is due to the very low fission product inventory of the reactor prior to operation at or near full power. Based on previous SNAP-8 and 10A reactor experience, it is reasonable to assume that 100 to 1000 watt hours of operation is sufficient to verify control drum operation, criticality margins and integrity of a flight reactor. Extensive engineering and qualification tests of non-flight reactors should be planned to verify conformance with design and operational performance specifications. Based on 12 days operation at 100 watts, the worst case radiological hazards (see Section 3) exclusive of a reactor excursion would result from a complete loss of vessel containment and would present a "safety marginal" (Reference 5-1) hazard to personnel and hardware.

Reactor excursions can also present potential hazards. The detailed effects of excursions on personnel are analyzed in Volume III, Parts 2 and 3. The mechanisms by which such an event can occur appear to be remote. Based on ZrH reactor design and SNAPTRAN tests it has been assumed that a "worst case" excursion during prelaunch could produce an energy equivalent of up to 100 MW-sec (Reference 5-2). Radiological characteristics of such an excursion are presented in Section 3. Where precautions, such as the implementation of controlled access areas are adhered to, the number of personnel affected would be very low. Accidents of this nature would be categorized "safety marginal to critical".

Inadvertent reactor criticality and quasi-steady-state operation are also potential hazards during the prelaunch phase. Radiological characteristics of these conditions are presented in Section 3. The radiation levels surrounding the reactor are considerably lower than those associated with an excursion. However, the indefinite duration of a condition such as quasi-steady-state operation requires that a means be provided to render safe a reactor in such a condition. A "safety marginal" category has been assigned.

The implementation of safety design features, such as control drum lockout devices, protective containment, and the strict adherence to procedures will essentially eliminate inadvertent criticality accidents. The use of "render safe and hazard isolation" emergency teams can provide additional nuclear safety during the prelaunch activities.

5.2.1.3 Other Hardware

Radiation hazards to personnel and equipment may emanate from other than the nuclear material just discussed. The operation of X-ray sources, laser beams, and electro-magnetic radiation emanating from telemetry equipment must be controlled and the proper warnings displayed. No additional attention is given these devices in the prelaunch evaluation. For the most part, these devices are radiation emitters only while operating and preventative operating procedures can be applied effectively.

5.2.2 NON-NUCLEAR HAZARDS

Nuclear hardware operations involve not only nuclear hazards, but also several non-nuclear hazards. Of particular interest during prelaunch are the thermal hazards associated with isotope heat sources and the reactive and corrosive characteristics of liquid metals utilized as coolants in reactor power modules.

5.2.2.1 Liquid Metal Hazards

What may prove to be a more difficult problem during prelaunch operations than the radiation hazards of a reactor power module is the presence of rather significant quantities of liquid metals within the coolant loops. A 330 kWt ZrH Brayton cycle power module employing a liquid metal radiator contains a NaK-78 inventory of over 240 kg (530 lb). Figure 5-2 illustrates the liquid metal loops of a typical ZrH Brayton Cycle power module. It is assumed

that the complete reactor power module would be assembled before shipment to KSC. All NaK loops would be filled before final acceptance tests at the factory and would remain filled throughout all subsequent operations including all activities at KSC (Reference 5-3 and 5-4).

Prelaunch operations require special precautions and handling to prevent leaks, liquid metal fires, corrosion and oxidation. The liquid metal, NaK-78, reacts with a number of metals, gases and liquids, including water and oxygen (Reference 5-5). Opening and repairing of coolant lines and heat exchangers containing liquid metal must only be accomplished in closely controlled inert environments under strict procedures and regulations. At present, major repair should be confined to the factory environment where adequate facilities are available. In addition, special double containment design with an inert cover-gas environment should be provided the power module where feasible, to prevent the presence of moisture and other oxygen sources during prelaunch operations and possible failure conditions. Non-liquid metal radiators should be considered where performance and configuration requirements permit. Where NaK is only used in the primary coolant loop, NaK quantities are substantially reduced and provisions for double containment are simplified.

Where liquid metal is present, it is mandatory that proper fire fighting equipment be provided. The normal fire extinguishers such as water, CO_2 and carbon tetrachloride are incompatible with liquid metal systems. Dispensing devices containing calcium carbonate, impregnated sodium chloride or their equivalent must be provided (Reference 5-5). A thorough study and experimental program is recommended to provide suitable substances and procedures in suppressing liquid metal fires in the vicinity of booster/spacecraft combustibles and propellants. Additional discussion concerning liquid metal handling and fire protection is contained in Section 5.2.6.2.

5.2.2.2 Thermal Hazards

In general, reactor power modules do not present potential thermal hazards prior to operation. A discussion of the operational and post-operational thermal hazards is presented in Section 6.3.1.

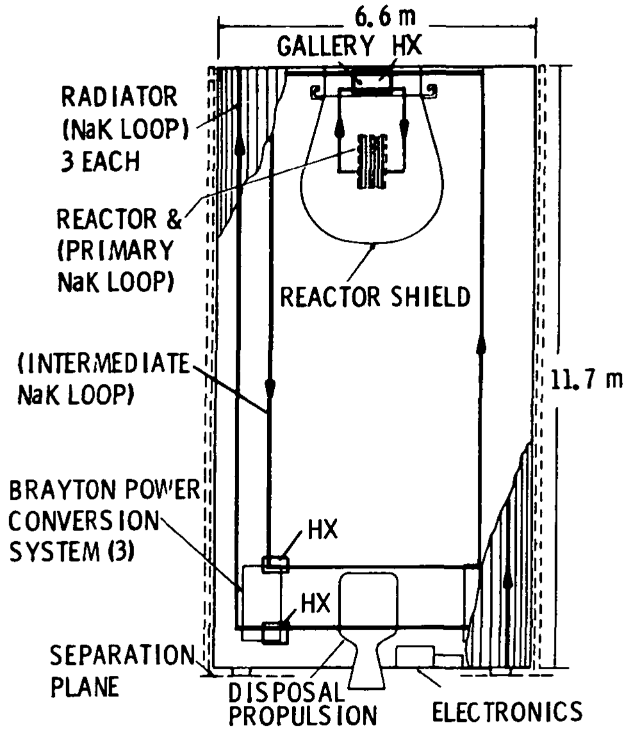


Figure 5-2. Simplified Reactor Power Module NaK Loop Diagram

Isotopes differ from a reactor in that they are a continuous source of thermal radiation energy as well as nuclear radiation. The thermal hazard is largely dependent on the quantity and type of isotope and the inherent heat transfer characteristics associated with packaging. The thermal output of several isotopes and heat sources is shown in Table 3-10 and 3-11 in Section 3-8. Equilibrium operating temperatures are on the order of $1500^{\circ}K$ (e.g., the Multi-Hundred Watt fuel capsule). However, most isotopes require cooling to below $420^{\circ}K$ ($300^{\circ}F$) in the natural open air environment to prevent capsule corrosion and reduce ignition potential of propellants such as hydrazine. Isotope sources with high surface temperatures present a hazard to personnel and surrounding materials. Therefore, design, handling and procedural provisions are required to reduce the potential hazards. Packaging and handling of isotopes are discussed in Section 5.2.3.1.

5.2.3 PACKAGING, TRANSPORTING AND HANDLING

The transporting and handling of nuclear hardware at the launch center can be simplified with proper consideration given to design, packaging and shipping techniques at the point of manufacture and final assembly.

Shipping containers must be designed in accordance with AEC Manual Chapter 0529, Safety Standards for Packaging of Radioactive and Fissile Materials (Reference 5-6), and with the Department of Transportation (DOT) regulations in Volume 33, Number 194 of the Federal Register (Reference 5-7). A DOT Special Permit must also be obtained for the shipment of all nuclear material.

Shipping regulations classify NaK as "non-exempt flammable-solid." As a result, the transportation of NaK in interstate commerce by land or water is subject to the "Dangerous Articles" regulations of the Interstate Commerce Commission. Transportation of liquid metals in civil aircraft is regulated by the FAA and is presently restricted to quantities of 11 kg (25 lb) or less in non-passenger aircraft.

5.2.3.1 Isotopes

The shipment and storage requirements of isotope heat sources differ depending on their size and heat source encapsulation technique. Radioisotopes continuously produce thermal energy and their temperatures rise until equilibrium is reached with the external environment. When sufficient isotope mass densities exist, a means of cooling is required (passively finned, air circulation, flowing liquid, etc.). At prelaunch conditions, it is generally advisable to keep capsule surface temperatures down below $420^{\circ}K$ ($300^{\circ}F$) to prevent capsule creep, minimize ignition sources and simplify handling and accessibility. Recent capsult designs employing refractory metal encapsulation necessitate the use of an inert gas environment to prevent oxidation at elevated temperatures. In addition to the cooling and inert gas provisions, container design should also prevent critical mass accidents under all conceivable stacking and packing situations.

Two examples of shipping and storage techniques representing different approaches are illustrated in Figures 5-3 and 5-4. Each provides for cooling, penetration protection to prevent breaching the capsules and prevention of critical mass accidents from packing or stacking of multiple units too close together. Figure 5-3 shows the handling and transportation technique proposed in the analysis of the shipment of the Large Heat Source Brayton cycle power system as defined in a recent study performed by NASA and the AEC (Reference 5-8). A specially equipped railroad car was to be provided for the shipment of a number of PuO_2 fuel capsules. The final assembly of the capsules into the heat source would be done in a Nuclear Assembly Building at KSC. Each shipping and storage container would hold three fuel capsules with provisions for adequate separation distances for prevention of a critical mass. Cooling units were provided on the railroad car to circulate cooling fluid through the shipping containers. Such a system could also serve as a storage facility if the need arose.

Back-up electrical power systems for a Space Base or prime power systems for a 25 kWe Space Station may utilize the Isotope Brayton power system. Particular attention should be given to the technique just described.

Individual heat sources such as those provided for a potential waste management system could be shipped and packaged similar to the procedure utilized in the SNAP-27 fuel capsule containment shown in Figure 5-4. The SNAP-27 heat source was passively cooled within a finned cask and like other heat sources, when integrated with the spacecraft, required pad cooling to reduce ignition source potential.

Tracer isotopes used on a Space Base provide no significant radiological hazard, but adequate protection must be given to insure against breakage and spillage. Double walled containers and self sealing covers have potential application. Containers must be appropriately marked and stored in isolated areas. The use and handling of liquid tracers in the space environment is discussed in Section 7.3.2.

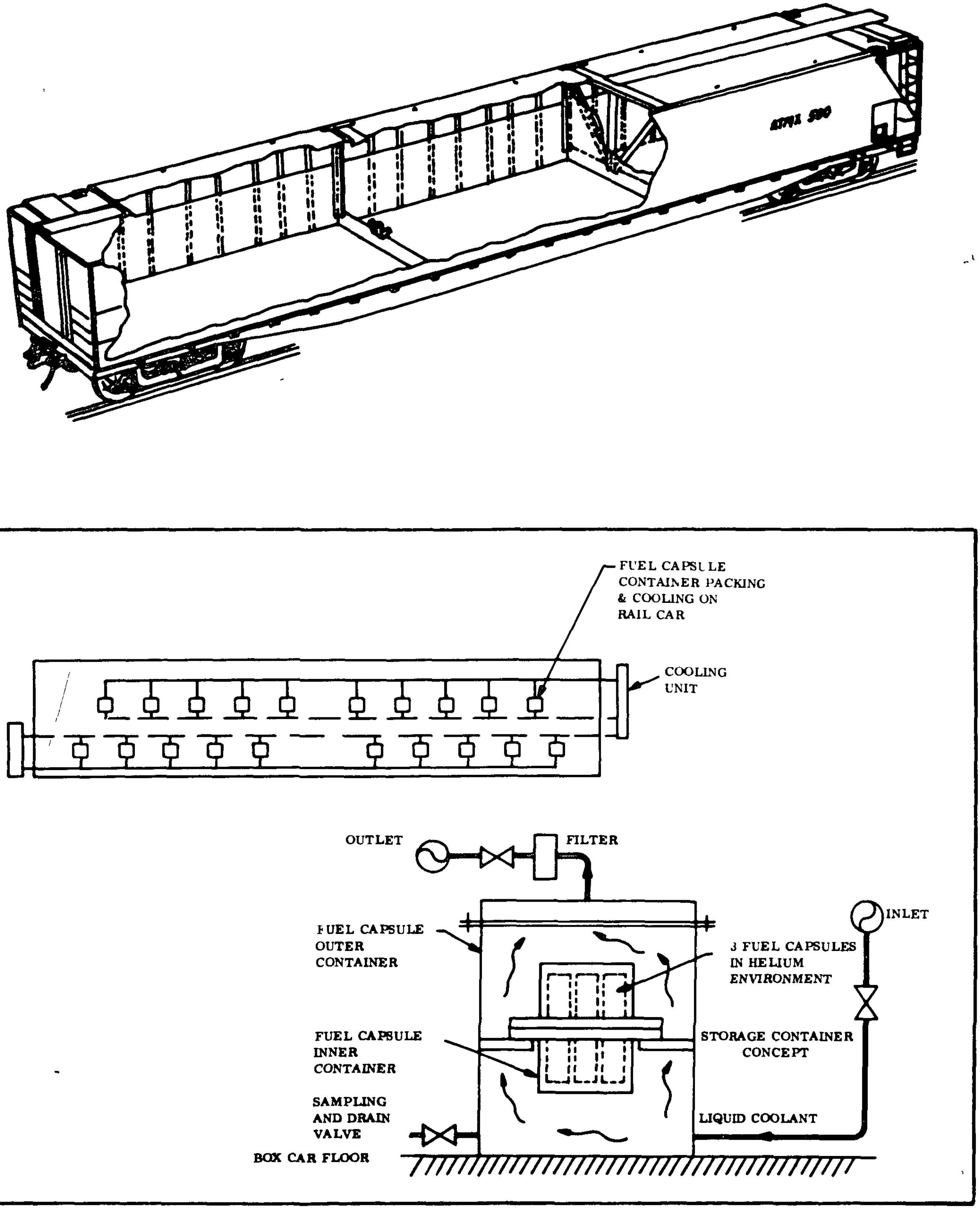
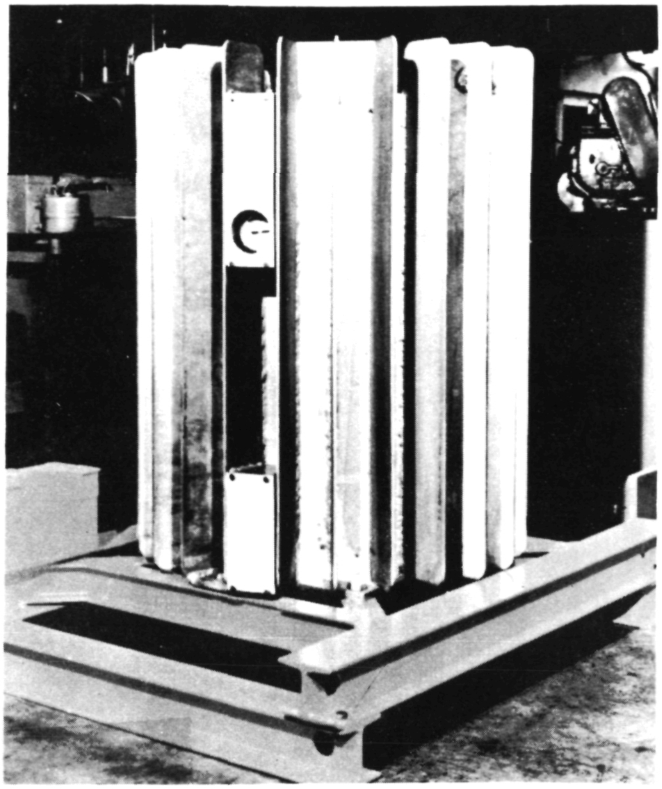
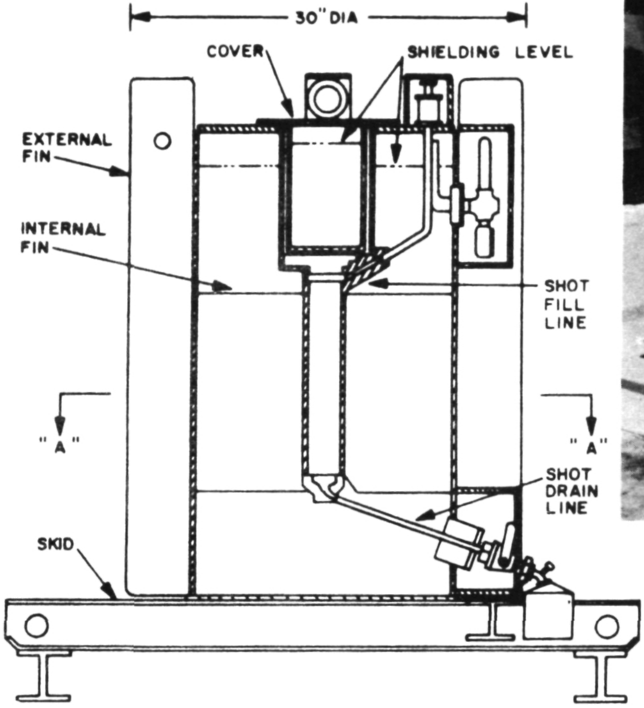


Figure 5-3. Isotope Brayton Fuel Capsule Shipping and Storage Concept





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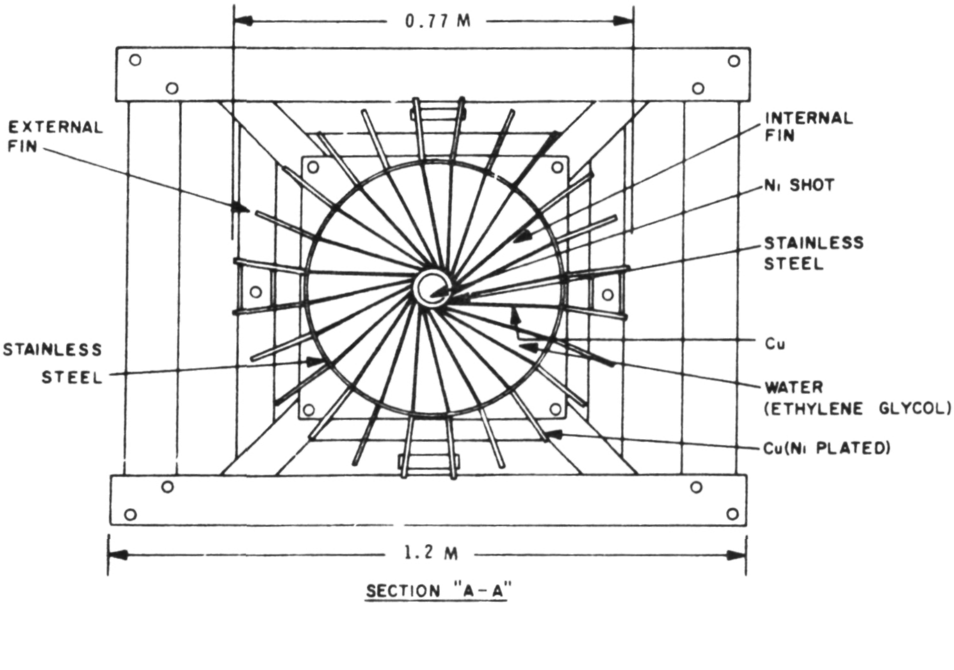


SECTION "A-A"

Figure 5-4. Ground Shipping Cask SNAP-27 Fuel Capsule

The handling of individual isotope heat sources generally requires the use of long handled tools to reduce the possibility of burns and minimize the radiation environment. Temporary shields can further reduce radiation doses to workers involved in isotope assembly and prelaunch operations. No standard universal procedures apply to all situations as the radiation levels, allowable work times and thermal environments are dependent on fuel makeup and quantity. $^{238}PuO_2$ fuel capsules are particularly adaptable to ground handling solutions. However, when handling Curium-244 or other similar isotopes, additional precautions must be observed as the radiation levels can be significantly higher. Under all circumstances radiation monitoring and individual personnel dosimetry are required.

5.2.3.2 Reactor Power Modules

The packaging, transportation, storage and handling of reactor power modules will be quite different from isotope systems. Assuming low power critical tests were performed several weeks prior to shipment to the launch center, the normal reactor radiation and thermal hazards at KSC are low. Cooling provisions and special radiation shields are not required.

However, considerable attention must be given to the safe handling of the liquid metal coolant within the reactor and coolant loops. The transportation and prelaunch operations are conducive to the development of liquid metal leaks which can conceivably lead to fires and reactor power module damage. The principal and most effective safeguards that can be provided involve safe and simplified handling techniques which incorporate maximum environmental protection. Where design and performance requirements permit, non-liquid mental coolant loops should be considered. Double containment of liquid metal loops can greatly increase the environmental protection.

It is anticipated that the reactor power module will be shipped and completely loaded with NaK-78 liquid metal coolant. This procedure does not necessarily eliminate the necessity for a liquid metal servicing facility at the launch center. Discharging and rendering safe a leaking or damaged power module prior to shipment back to the point of manufacture may be required. Further discussion regarding the requirements and use of such a facility at the launch center is presented in Section 5.2.7.3.

Transporting and handling of a power module is somewhat complicated due to the large size and mass of the structure, and the desirability of continuous environmental protection. The Space Base power modules are large structures approximately 6.6 m in diameter, 12 m in length, comprising a mass of over 30 t (65 Klb) each. Most of the mass is in the reactor and shield which are located at one end of the module (see Figure 5-2). Vertical handling, transporting and storing is preferred, but this mode requires a complex carrier vehicle, facility and ground support equipment. Horizontal handling and transporting lessens the impact on the carrier and facilities, but imposes rather severe structural requirements to support the reactor and shield within the power module. An adaptation of the horizontal to vertical erection technique used with the Titan II stages at the Eastern Test Range (ETR) could be considered. Using this procedure, the power module would be shipped and checked out in a horizontal cradle and erected vertically within the cradle prior to integration with the launch vehicle at the launch site or within the VAB. (This cradle could also be used as, or in conjunction with a "transfer module" recommended for use with the Space Shuttle in Volume IV Part 1.)

Figure 5-5 illustrates the application of the horizontal to vertical technique incorporated into an integral transportation trailer and storage container "transporter". The power module would be supported by a transfer cradle within the transporter. The transfer cradle would provide the added support required of the power module in the horizontal position and would only be removed after vertical integration with the booster. The transporter must be equipped to monitor radiation, humidity, temperature and pressure and must provide the necessary inert cover gas environment, fire protection, alarms and warnings. Depending on the power module size, the transporter would be used for transport by airplane, barge, rail and roadway. It would also serve as the storage container and provide accessibility for checkout and component assembly. A somewhat similar device has been successfully used by NASA in transporting, handling and storing the NIMBUS spacecraft from the point of manufacture to the launch complex. The Air Force employs a similar technique in the transporting and handling of the operational Minuteman missiles. <u>The reduced handling and increased environmental protection possible with the transporter concept provides significant safety advantages.</u>

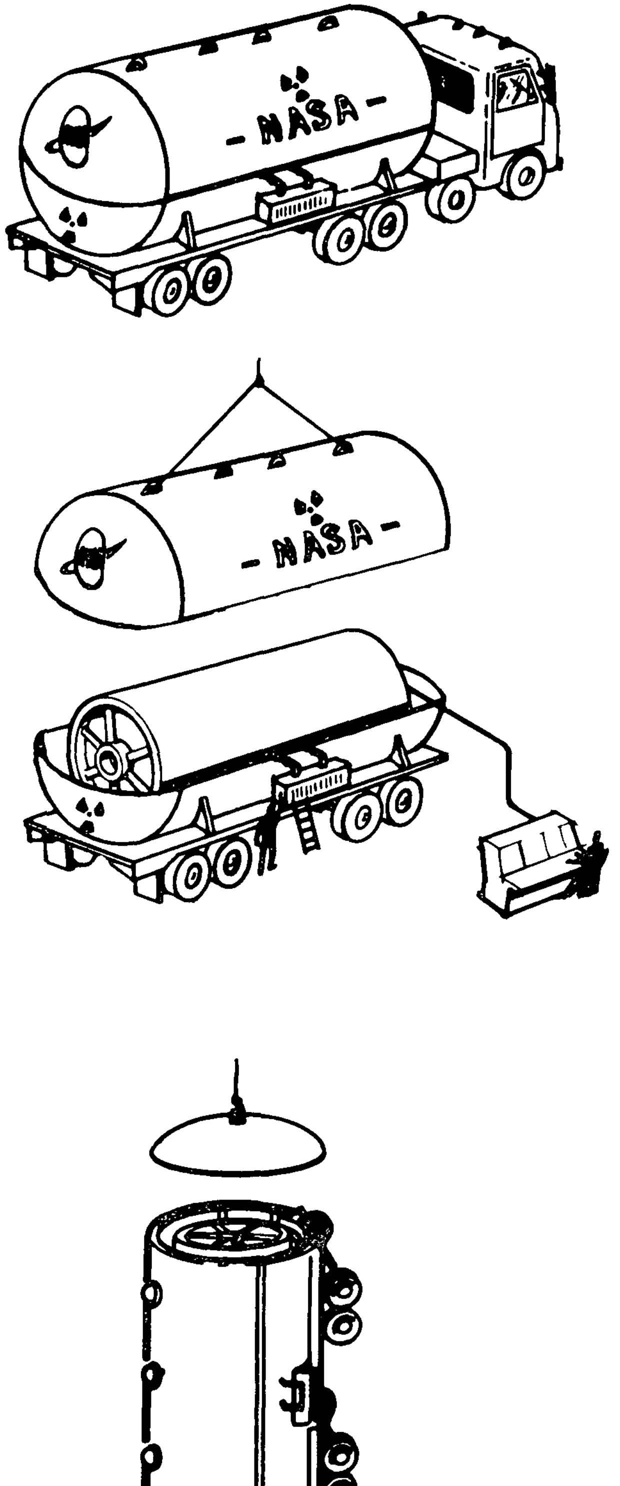


Figure 5-5. Reactor Power Module Transporter

Table 5-2. Guidelines for Packaging, Transporting and Handling Nuclear Hardware

GENERAL

- Provide shipping containers and procedures in accordance with AEC Manual, Chapter 0529 and The Department of Transportation Regulations in Volume 33 No 194 of the Federal Register
- Provide personnel dosimetry and radiation monitoring wherever nuclear material is present
- Select routes to avoid heavily traveled and populated areas
- Provide escorts and warning devices during ransportation
- Use cross-trained personnel experienced in handling nuclear material
- Endure strict adherence to procedures, warnings and controlled access areas
- Provide secure tie-downs and proper positioning of nuclear hardware on transportation beds to prevent the compaction of fuel into critical masses and possible separation from the carrier
- Provide emergency equipment and personnel who can quickly render safe and supervise the handling of damaged nuclear hardware

REACTOR

- Consider provision of a modular reactor powerplant design by the addition of a separable heat exchanger in the primary loop and a separable disposal package
- Consider vertical module stacking and mating
- Provide integral transport and storage containers which combine shock protection, environmental protection, status and radiation monitoring, fire protection and bouyancy in a single unit
- Provide double containment of liquid metal components where feasible
- Provide control drum lock-out devices
- Minimize use of liquid metal coolant loops where design and performance requirements permit
- Provide special fire fighting capability for liquid metal systems

ISOTOPE

- Provide redundant and back-up cooling systems where auxilliary cooling is required
- Provide structural spacing to prevent criticality and provide container rigidity for penetration free containment
- Provide double wall containment for isotope tracers

A somewhat different and practical solution to the transportation and handling problem is a design which features separation of the reactor powerplant into modules which can be mated (stacked) vertically on the booster. Three basic modules: (1) Reactor/Shield, (2) Radiator and Power Conversion System, and (3) Disposal System, constitute the powerplant as shown in Figure 5-6. This configuration requires a separable primary heat exchanger to avoid breaking into liquid metal lines during assembly or replacement. Transportation, handling and environmental protection concepts can be simplified since the reactor and shield can be separately packaged within a relatively small envelope. Therefore, the hazards associated with the radiator and disposal systems would not affect the reactor during transportation and initial prelaunch activities.

The separable heat exchanger also provides advantages for in-orbit reactor replacement and disposal. Reactor disposal orbit lifetimes can be significantly increased (approximately a factor of ten) by the separation of the reactor/shield from the rest of the system. The increased orbital lifetimes resulting from a separation of the reactor/shield are discussed in Section 7.3.4. <u>The separable heat exchanger can be a significant design feature affecting nuclear safety in prelaunch and orbital operations and should be given careful consideration in future space reactor power module designs.</u>

Accidents occurring during transportation could cause damage to the power module. Damage to the control drum actuator system may cause inadvertent control drum rotation resulting in a reactor criticality or excursion. Defined modes leading to criticality or an excursion during transportation and handling are difficult to postulate; nevertheless, the potential exists. <u>The incorporation of a mechanical control drum locking device can prevent drum rotation during transportation and handling and can also be applied in subsequent phases.</u>

5.2.3.3 Packaging, Transporting and Handling Safety Considerations

The guidelines considered important to the safe packaging, transporting and handling of nuclear hardware during prelaunch operations at the launch center are listed in Table 5-2. These guidelines are also presented in Volume V, "Nuclear System Safety Guidelines".

5.2.4 NUCLEAR STORAGE

The nuclear hardware would arrive at KSC by the most appropriate carrier depending on conditions and configuration at that time. It should be transported directly to a Nuclear Assembly Building (NAB) which also serves as a storage facility (see Figure 5-7 and Section 5.2.7.2). KSC storage times of a few months to several years may be required of isotope heat sources and nuclear reactor power modules in order to provide a replacement in-orbit time of approximately 12 days. Nuclear hardware in storage should be held in a state of readiness (1-2 days preparation time) for integration with the launch vehicle. Due to potential scheduling difficulties and the need for back-up systems, it is postulated that a maximum of three reactor power modules, several small isotope heat sources and possibly an entire complement of fuel capsules for two large heat source power systems may have to be stored at one time. Cooling, environmental control, and anti-criticality spacing must be maintained. The reactor power modules could be stored within the environmentally controlled transport trailers in the NAB. The NAB could also be designed to provide isotope heat source storage capability. An ATMX Series 500 railcar, considered for use by the AEC for shipment of large heat source fuel capsules, could be retained on a railroad siding adjacent to the NAB as a storage facility.

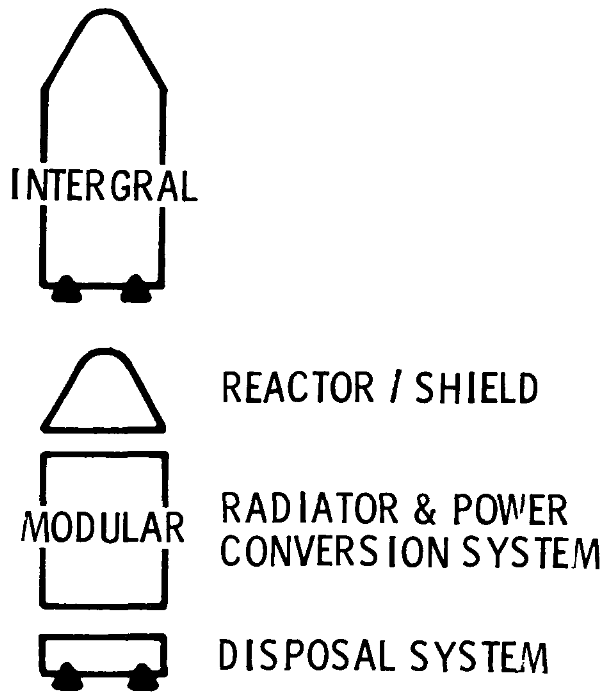


Figure 5-6. Modular Concept

Routine airborne and surface radiation and contamination measurements must be made while the nuclear hardware is in storage. A plutonium air monitor (RADECO model RAD-221A or equivalent) whose selectivity detects the alphas emitted from plutonium-238 heat sources is recommended, in addition to neutron and gamma dosimetry. Permanent radiation monitors are also required and must be integrated with alarm systems.

Periodic checkout and status monitoring of the nuclear hardware is advisable during storage. Where feasible, consideration should be given to checkout/monitoring of systems without removing environmental enclosures. The facility requirements and detailed radiological monitoring requirements required during storage are discussed in Sections 5.2.7.1 and 5.2.7.2, respectively.

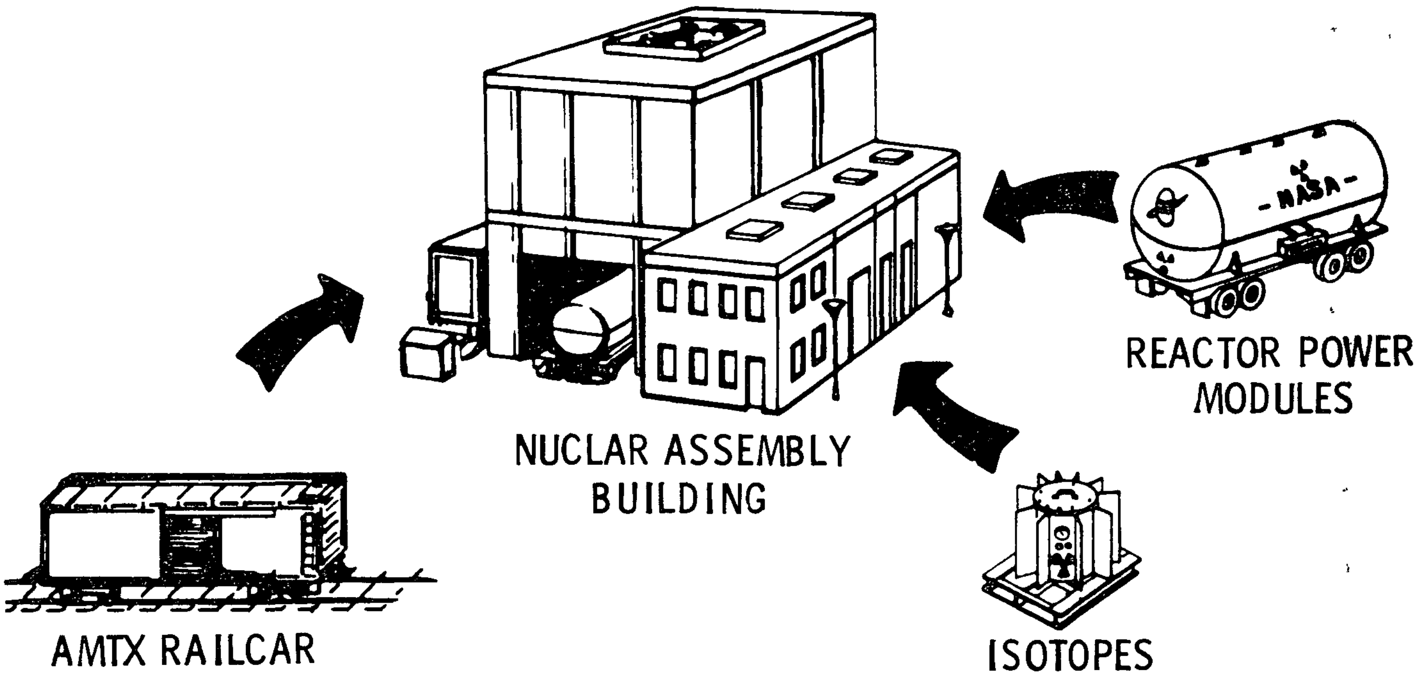


Figure 5-7. Nuclear Assembly Building Storage Operations

5.2.4.1 Nuclear Storage Safety Considerations

Table 5-3 summarizes the important considerations which should be applied in the safe storage of nuclear hardware at the launch center.

5.2.5 PRELAUNCH OPERATIONS

The prelaunch operations described in this section include the principal receipt, assembly,

Table 5-3. Guidelines for Storage of Nuclear Hardware

GENERAL

- Consider use of a nuclear assembly building as the prime storage facility
- Storage provisions must accommodate lifetimes of a few months to several years
- Segregated storage should be provided insofar as possible
- Storage should be provided in facilities equipped with adequate environmental control (low humidity, dry clean air, no water collection on floor, no sprinklers)
- Provide fire protection compatible with nuclear material and liquid metal systems
- Provide routine radiation measurements
- Provide permanent radiation monitoring and alarm systems
- Provide periodic checkout and status monitoring capability while in storage
- Provide nuclear hardware readiness capability of 2 days
- Store ordnance and thrusters in a separate facility

REACTOR

- Consider storage of power modules in transporters within separated storage bays

ISOTOPE

- Store isotopes with proper anti-criticality spacing provisions
- Consider use of shielded areas to minimize radiation in adjacent bays
- Provide redundant and or back-up cooling where auxilliary cooling is required
- Consider use of AMTX type railcars for back-up storage

checkout, integration and launch countdown activities associated with the nuclear hardware at KSC. Reference is made to the general ground flow plan, Figure 5-1. Normal reactor power module prelaunch operations are expected to comprise approximately 90 days. However, replacement hardware should have a 10 to 12 day prelaunch timeline to minimize down-time in orbit. The prime discussion is concerned with the reactor power modules. The isotopes associated with the reference Space Base do not present significant nuclear safety problems during prelaunch operations. However, consideration has been given to nuclear safety of the larger quantities of isotope which could be employed on future missions (e.g., Isotope Brayton Heat Source). The safety of the X-ray hardware has not been

emphasized, as conventional techniques can be employed in the installation and test of this equipment within the Space Base core module.

5.2.5.1 Nuclear Assembly Building Operations.

The principal prelaunch operations involved with nuclear hardware prior to integration with the launch vehicle include:

- Receipt and Inspection
- Subsystem Checkout
- Assembly
- System and Integration Checks
- Storage

It is feasible that these operations could be accommodated within an existing KSC facility such as the VAB, the Manned Spacecraft Operations Building or the Pyrotechnic Facility. However, the nuclear and liquid metal hazards involved and the nuclear safety requirements such as segregated storage, controlled accessibility and special environmental control dictate consideration of a separate and isolated nuclear facility.

For study purposes, the use of a Nuclear Assembly Building (NAB) has been assumed. A description of the typical requirements of such a facility are presented in Section 5.2.7.2. Actual checkout, assembly and test time for a typical reactor power module within this facility is expected to comprise approximately 20-30 days.

5.2.5.1.1 Receipt and Inspection.

The power module would arrive at the NAB within a transporter. A comprehensive visual inspection would be performed and recording instruments would be checked for shock, vibration and environmental conditions - temperature, humidity, air chemical composition and radiation. Shipping covers are opened or removed and an inspection made of the power module for visual damage, fluid leaks, system integrity and cleanliness. Reactor control

safety devices are checked. Consideration should be given to the use of the Transporter during all phases of inspection, checkout and storage; providing a universal piece of hardware equipped with proper status and safety instrumentation and structural support. Provision must be made for the discharging and purging of the liquid metal loops outside the confines of the NAB so that in case of a leak, the system could be safed for shipment to a repair facility. After completion of receipt and inspection activities, the power module is ready for systems checkout or short term storage. Purging the enclosure and replacement of desicant material and filters should precede placement in storage. The radiation hazards of a reactor power module during receipt and inspection operations are considered "safety negligible" provided procedures are rigidly followed and environmental and control drum safety features are incorporated.

Receipt and inspection of isotopes consists primarily of investigation for shipping damage. This can normally be accomplished by inspecting individual capsules for integrity, surface defects and tolerances. Glove box inspection is required for refractory metal encapsulated heat sources to prevent oxidation. In other instances, such as the technique employed for the SNAP-27 fuel capsule, (Reference 5-9 and 5-10) handling receipt and inspection can be accomplished in a clean open air environment. Smear (wipe) tests and air monitoring must be performed prior to these operations. Strict adherence to procedures allow for the safe handling of isotopes. These procedures include: (1) limiting the distances and time an individual is allowed for observation, (2) stacking/packing limits to prevent critical masses, (3) the use of proper handling and protective hardware, (4) radiation and temperature monitoring, (5) isotope cooling, and (6) use of the two-man "buddy" system during all nuclear operations.

Where other than passive cooling is required, backup cooling systems must be provided. The radiation and thermal hazards are dependent on the type of isotope fuel used. The majority of heat sources being developed employ $^{238}PuO_2$ isotope as fuel. The proposed Isotope Brayton backup power source would most likely consist of about 120 kg of $^{238}PuO_2$ (Reference 5-8). However, other isotope fuels offering performance advantages may be employed. The safety program must be responsive to the nuclear material (isotope) that is to be used.

5.2.5.1.2 Subsystem Checkout

Prior to integration with the launch vehicle or placement in storage, a series of subsystem verification tests would be performed to assure the integrity and functional operation of the power module. Consideration should be given to the performance of these tests with the power module in the Transporter (Figure 5-8). Semi-portable test equipment could be employed, portions of which could be used in the VAB and at the launch pad. Such procedures reduce the need for additional handling and ground support equipment and minimize the possiblities of incurring damage and leaks in liquid metal coolant lines. The first series of tests consist of electrical continuity checks of wiring harnesses and connectors and functional checks of all monitoring circuits and subsystems to the extent possible without activating the reactor control drum system. No mechanical control drum lockouts are provided on the reference reactor. They should, however, be considered a prime ground safety feature and be incorporated for these tests. (Control drum lockouts are also recommended during orbital buildup and to assist in positive reactor shutdown and disposal.)

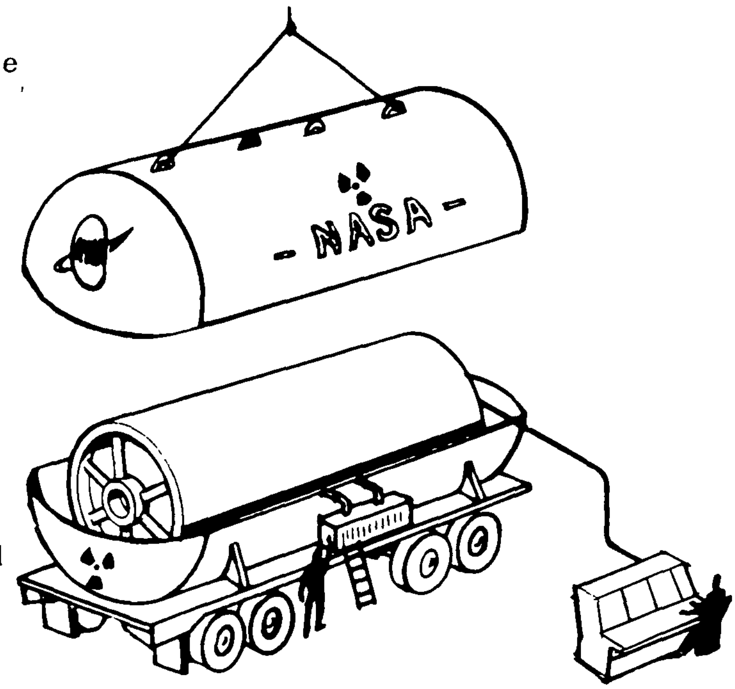


Figure 5-8. Checkout and Subsystem Tests

During the second series of tests, the NaK and gas heat transfer coolant systems (reactor primary loop, intermediate loop, and radiator loops) should be circulated to verify functioning of the PCS, valves and Electromagnetic (EM) pumps and provide pressure and leak tests of all lines and connections. These tests are performed without reactor power, possibly requiring the use of electrical heaters. Several of these electrical and fluid system tests should be repeated every 6 months while a power module is in storage as well as immediately upon removal from storage for flight.

The third series of tests involves a check of reactor control drum and circuitry operation. Control drum interlocks (if provided) would be temporarily removed. Provision for individual removal of interlocks should be considered to prevent movement of more than one drum at a time. Reactor control response and actuator and drum operation is verified by individually stepping the drums one or two steps and then backing off to the full out position. The reference reactor does not provide a positive method of identifying control drum position, but rather anticipates a step of the drum for each pulse sent. A possibility exists that a drum could freeze or temporarily stick in a given position without the condition being detected when operating or testing in the sub-critical region. This would be the case during the prelaunch checks, where control drum position or correct movement and control could not be ascertained. A means of detecting control drum position should be provided for ground checkout, which would also increase the safety and control of reactor start-up and other reactor operations in orbit.

No criticality tests should be made at KSC, these having previously been successfully completed prior to shipment. Except during the checks of the control drums and circuitry, the drum lockout devices must remain inserted at all times until initiation of the startup sequence in orbit. Nuclear hazards during these subsystem checks are categorized "safety negligible" if procedures and design considerations are followed.

With suitable containment (Section 5.2.3.1), subsystem checks of isotope tracers would not constitute a significant nuclear safety hazard. However checks of candidate isotope heat sources require special precautions as discussed in the previous section to minimize radiation to personnel and maintain adequate thermal protection.

5.2.5.1.3 Assembly

The reference power module does not permit a separation of the radiator from the reactor/shield at KSC. The Disposal System located at the extreme end of the power module, should be designed to be shipped separately without its rocket motors and ordnance. This feature would permit modular replacement in orbit and avoid bringing explosives into the NAB. The Disposal System minus its rocket motors, would be assembled to the power module in the

NAB for system integration tests. Assembly of special flight components and repair or replacement of power conversion system hardware could take place at this time. The inert cover gas environment for the power module can not be maintained for all tests within the NAB. Special precautions should be taken to assure maximum environmental control of the facility and the accessibility of liquid metal fire fighting equipment during operations when liquid metal is present.

If the power module were to employ a separable heat exchanger, as discussed in Section 5.2.3.2, final assembly may best be performed at the time of integration with the launch vehicle (either within the VAB or at the launch pad). This procedure would eliminate the need for, and reduce the hazards involved in, the transport and handling of a large horizontal or vertical stack, but would not permit a complete mechanical and electrical integration check until mating with the launch vehicle. Inter-connecting cables and interface adapters/simulators could be use for preliminary checks with the launch vehicle, but would not eliminate the need for final integration tests with the launch vehicle on the Mobile Launcher.

The assembly of a large isotope heat source (Figure 5-9) should be performed behind a shielded facility segregated from the reactor power module assembly area.

5.2.5.1.4 System and Integration Checks

The power module would be given a series of preliminary integration tests within the NAB to assure mechanical and electrical compatibility with the launch vehicle and ground support equipment. Power module system interface tests would be performed during which simulated launch vehicle and power module interface electrical signals are sent, received and sequenced for

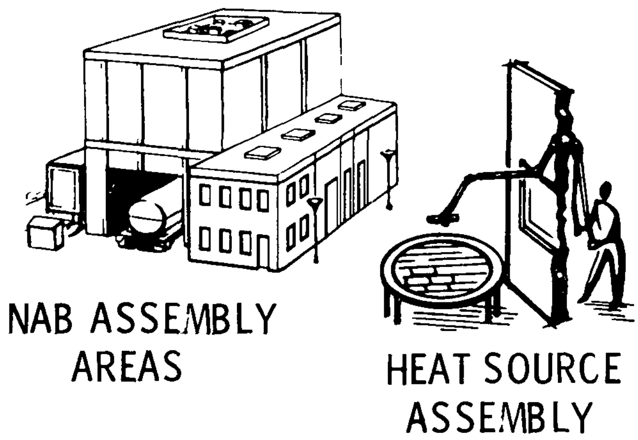


Figure 5-9. Large Heat Source Assembly Operations

prelaunch and in-flight operation simulation. Mechanical and electrical interfaces are checked. Mating interface adapters are used to check for surface roundness and attachment compatibility (Figure 5-10). Electrical interface checks include umbilical connections and telemetry checks verifying ability to receive and transmit on "up" and "down" links. These activities will not present a significant radiation hazard as long as nuclear safety regulations are followed. A "safety negligible" category has been assigned.

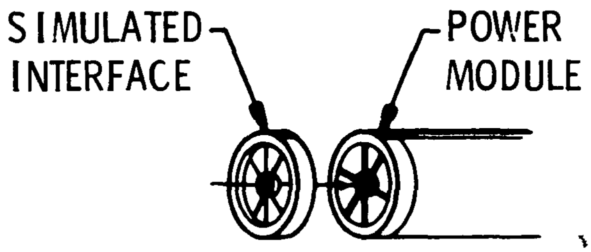


Figure 5-10. Preliminary Interface Integration

At the completion of these tests, the power module is readied for transport and integration with the launch vehicle or put in interim storage. Preparation for transport includes 1) the safing of all ordnance and control systems, 2) preparation of protective shrouds, 3) purging and closing of the Transporter or containment vessel, and 4) Transporter instrumentation checks.

5.2.5.1.5 Nuclear Assembly Building Operations Safety Considerations

Table 5-4 summarizes the important considerations which should be applied in the receipt, inspection, and checkout activities of nuclear hardware at the launch center.

5.2.5.2 <u>Vehicle Assembly Building Operations</u>

The principal operations within the Vehicle Assembly Building (VAB) high bay area are the integration and combined systems tests of the launch vehicle stages, the nuclear payload and support hardware (Figure 5-11).

Table 5-4. Guidelines for Operations within the Nuclear Assembly Building

GENERAL

- Limit and regulate personnel activities in radiation areas
- Use proper handling tools and protective clothing
- Provide personnel dosimetry, permanent and portable radiation monitoring
- Employ two-man "buddy" system
- Provide multiple escape routes
- Maintain environmental control provisions insofar as possible
- Do not permit ordnance and disposal rocket motors within NAB facility
- Maintain liquid metal and nuclear fire fighting capability
- Perform mechanical and electrical interface checks prior to transport to the VAB or launch pad
- Provide adequate isolation (segregation) for checkout and storage of the various nuclear hardware

REACTOR

- Consider use of universal transporter during inspection, checkout and storage
- Provide liquid metal purging and discharging capability outside confines of NAB
- Employ mechanical control drum lockout devices on reactor power modules
- Restrict control drum movement to a single drum during testing
- Provide means of sensing control drum position
- Consider use of separable heat exchangers to permit use of modular design

ISOTOPE

- Adhere to nuclear hardware packing limits and provide anti-criticality containers
- Provide backup cooling systems for isotope heat sources

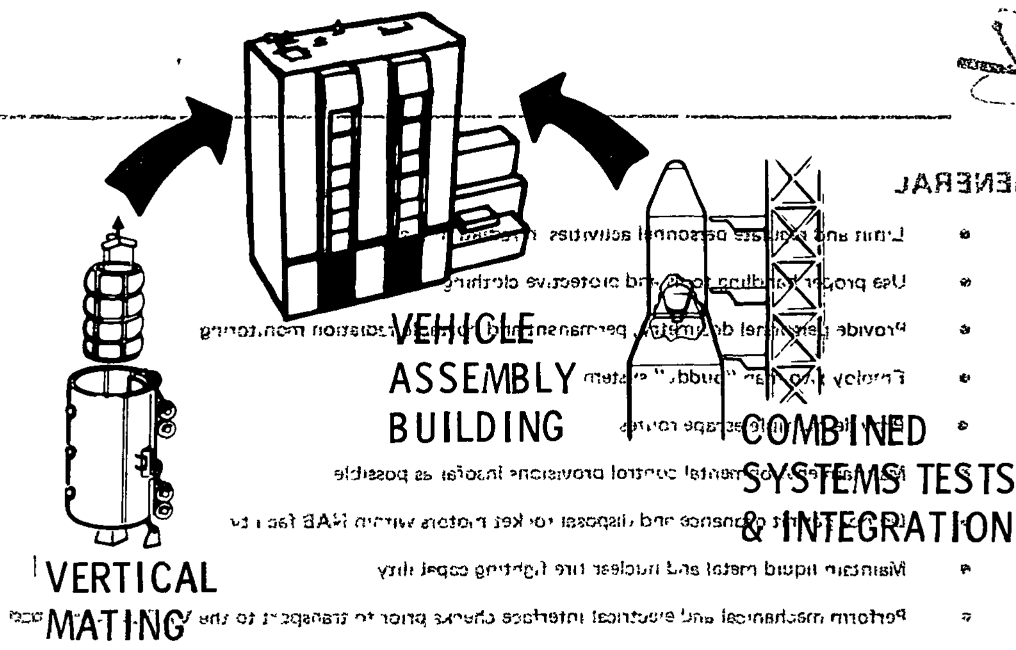


Figure 5-11. VAB Operations

5.2.5.2.1 Integration with Launch Vehicle

The extent of the integration tests to be performed within the VAB are dependent on the launch vehicle, nuclear payload requirements, and facility safety constraints. The baseline launch vehicle is the Saturn INT-21. However, the Space Shuttle could be used as a launch vehicle if the reactor power module were designed to be modularized, as discussed in Section 5.2.3. (An evaluation of nuclear safety aspects of the Space Shuttle in transporting a reactor power module is contained in Volume IV.)

Integration of the nuclear hardware includes mating to the launch vehicle, electrical and mechanical compatibility checks and integration with ground support equipment. Preliminary checks would be conducted of control and telemetry links with the Range, Launch Control and Mission Control (Electromagnetic Interference tests are performed at the launch pad to verify compatibility with power module and ordnance circuitry).

The mating operation may prove to be the highest risk prior to launch, due to the potential for NaK leaks being caused during handling. The use of a well designed horizontal to vertical support cradle, which can be a part of a Transporter (shown previously in Figure 5-5), would reduce the possibility of damage and can also provide environmental protection. Figure 5-12 illustrates two proposed horizontal to vertical lift techniques. Environmental cover gas and purging capability would be switched from the portable system on the Transporter to the Mobile Launcher after mating is achieved and service arm umbilicals are connected.

A modular design employing a separable heat exchanger allows the mating and stacking of individual modules within the VAB or at the launch pad. A similar procedure would be employed with an Isotope Brayton power system. An auxiliary coolant system is an important element during these operations in maintaining the refractory metal heat source plate and fuel capsules below 420°K. This unit can be transferred with the heat source to the mating/integration level of the Mobile Launcher tower. The cooling system on the Mobile Launcher would then be connected, the auxiliary coolant system serving as a back-up. The radiation levels and thermal environment of a large heat source are such as to require the longer duration manned operations to be performed several feet from the source or behind temporary shields. Reference 5-8 should be consulted for additional details on these operations.

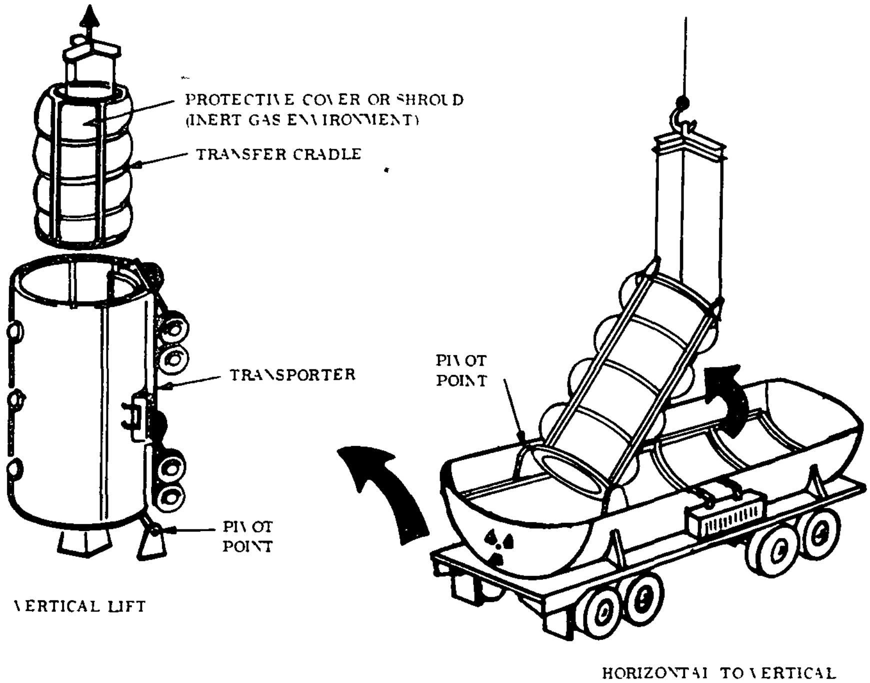


Figure 5-12. Use of Transporter During Lift and Mating Operations

Small isotope heat sources generally would not require extensive special operations. They could be installed in the core modules within the assembly areas or in cases where the isotopes are readily accessible and not required for system checks - installation with ordnance items is preferred. Auxiliary cooling systems within the core modules may be required prior to in-orbit operations.

5.2.5.2.2 Combined Systems Tests

The combined systems tests in the VAB consist of first, an interface and systems status check of the power module including umbilical disconnect and plug drop tests and secondly, a simulated countdown, launch and flight readiness demonstration of the entire vehicle. Only separation, command and control, telemetry and launch readiness go-no-go functions are required of the power module. Control drum actuators are not activated and lockout devices previously recommended should remain installed. The power module should remain within the environmental shroud. After completion of the tests, the entire vehicle is prepared for transfer to the launch complex.

* * * * * *

Two trade-off considerations have a direct bearing on VAB activities and are presented below:

1. VAB Versus Launch Pad-Nuclear Payload Integration. The normal radiation hazards of the reactor power module in the VAB are considered "safety negligible." The probabilities of inadvertent criticality and nuclear excursions are low and can be further reduced with the incorporation of mechanical control drum interlocks. However, accidents involving the nuclear hardware and liquid metal systems can occur and result in damage to equipment and injury to personnel. Possibly the principal hazards resulting from the reactor power module within the VAB arise from the necessity of mating, testing and transporting with a complete liquid metal inventory. (As previously stated, this hazard would be substantially reduced with the use of a non-liquid metal radiator.) The present fire protection systems used in the VAB are incompatible with liquid metal. Further discussion of the liquid metal fire protection requirements is contained in Section 5.2.6.2.

The potential hazards within the VAB can be eliminated by foregoing tests in the VAB and performing the equivalent operations at the launch pad. The functional tests required of nuclear hardware after integration with the launch vehicle are very limited, consisting mostly of support tests such as isotope cooling and reactor thermal shroud operation. Due to the constant radiation and thermal hazards associated with an isotope heat source and the minimum functional test required, it is recommended that isotope systems be integrated with the launch vehicle at the launch pad. Similar procedures should be considered for a reactor power module. The tests in the VAB would be performed with a simulated payload.

The reduced crane/hoist flexibility and the exposure to weather during mating are the prime disadvantages of integration at the launch pad. These disadvantages are particularly important considerations when massive components are involved, such as a reactor power module.

2. Dual Versus Single Reactor Power Module Launch. The use of the INT-21 affords the possibility of a dual power module launch. The power module radiator diameter would of necessity be reduced from the 6.6 m (21.7 ft) to less than 4.9 m (16 ft) to allow two modules within the INT 21 shroud envelope. This concept was proposed by NAR in Reference 5-11. The impact on nuclear safety of a dual power module launch is quite involved. Additional integration complexity is expected and the quantities of nuclear material and liquid metals are doubled. However, the increased risk caused by these factors is partially compensated by a reduction in risk since the dual power module launch only involves a single launch versus the two required in the previous case. The quantitative nuclear safety advantages of either mode could not be addressed in this study, but remain to be evaluated should future design options permit.

5.2.5.2.3 Vehicle Assembly Building Operations Safety Considerations

In order to minimize the hazards within the VAB, the design and operational guidelines presented in Table 5-5 should be considered.

Table 5-5. Guidelines for Operations within the Vehicle Assembly Building

GENERAL

- Conduct thorough evaluation of the necessity and desirability of integration and testing of nuclear hardware within VAB
- Install reactor power modules and isotope systems as late in the prelaunch sequence as possible
- Provide environmental protection during mating and integration operations
- *Use only experienced and cross trained personnel*
- Limit and regulate personnel and activities in radiation and liquid metal areas
- Provide personnel dosimetry, and permanent and portable radiation monitoring systems coupled with alarms and warnings
- Employ two-man "buddy" system where appropriate
- Provide multiple escape routes
- Provide nuclear procedures in the KSC Ground Safety Plan K-V-053 (Ref 5-12)
- *No smoking or eating should be permitted in nuclear areas unless specifically designated*

REACTOR

- Provide power module environmental protection by double containment and inert gas shrouds or bladders
- Conduct thorough evaluation of the incompatibility problem of the present VAB fire protection system
- Provide rapid response liquid metal leak detection and fire suppression equipment at the ground and payload levels of the Mobile Launcher
- Avoid the use of materials, gases and liquids that are incompatible with liquid metals
- Consider use of dummy power module for certain Launch Vehicle, VAB & ML integration activities

ISOTOPE

- Provide Isotope auxiliary and backup cooling systems compatible with the VAB and Mobile Launcher
- Integrate isotope systems at the Launch Pad (bypassing the VAB) where feasible

5.2.5.3 Launch Pad Operations

The principal operations involving nuclear hardware at the launch pad, as illustrated in Figure 5-13, include:

- Isotope Installation (Reactor Power Module Installation Optional)
- Integration with Launch Pad Ground Support Equipment and Range Systems
- Rocket Motor Installation
- Combined Systems and Overall Acceptance Tests
- Simulated Countdown Demonstration
- Ordnance and Ignitor Installation
- Launch Readiness, Countdown and Launch

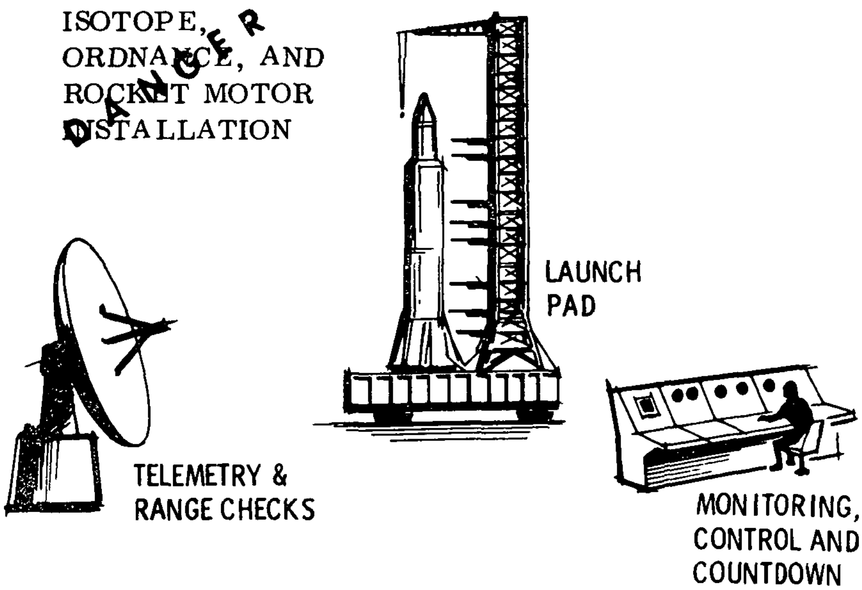


Figure 5-13. Launch Pad Operations

5.2.5.3.1 Reactor Power Module Operations

An objective of the power module launch pad activities is to keep operations involving the power module to a minimum. This objective becomes realistic when the launch pad test and preparation requirements of the power module are analyzed. In general, the power module activities are rather limited, the power module assuming nearly a "dormant" role (status monitoring only) until orbital operations begin.

Current processing of Apollo/Saturn V vehicles at the launch pad comprises a 75 to 85 day period with approximately 25 days specifically assigned to Spacecraft and Lunar Module tests and preparations (Reference 5-13). Several possible modifications or alternatives in current KSC operations could lessen reactor power module time at the launch pad and provide potential nuclear safety improvements, e.g.,

1. Conduct more launch vehicle and power module tests within the VAB to shorten the time at the launch pad.
2. Mate the power module with the launch vehicle late within the launch pad timeline.

The first consideration increases the hazard potential in the VAB as discussed in Section 5.2.5.2. Mating the power module late within the launch pad timeline can significantly reduce the exposure of the power module to undesirable environments and hence its vulnerability to potential prelaunch accidents. Mating of the power module could possibly be performed prior to loading of hypergolics and installation of ordnance (less than 25 days before launch).

The Mobile Launcher (ML) crane capability for such an operation should be confirmed (Reference 5-14). Wind loads during the lift to the 75m (250 ft) level must also be accounted for to prevent damage during the lift operation. Figure 5-12 illustrates a use of the Transporter with an internal protective shroud and cradle designed to protect the power module from damage during the mating/integration operation.

Modifications would be required of the service arms and work platforms to provide adequate accessibility, fire protection and environmental control. These and other facility considerations are discussed in more detail in Section 5.2.6.

The reactor power module should be protected from the vented H_2 and O_2 gases which occur during the propellant loading tests and the countdown because of the potential liquid metal reaction hazards present. Such protection could be achieved by use of environmental shrouds and on-pad purging with dry N_2.

5.2.5.3.2 Isotope System Operations

If an Isotope-Brayton Heat Source is to be launched, mating and integration is recommended at the launch pad to increase the safety of prelaunch operations (Reference Section 5.2.5.2). The actual loading of the heat source should be accomplished late in the countdown to 1) minimize radiation exposure to launch pad personnel, 2) reduce on-pad cooling time and restricted accessibility of operations and launch pad personnel and 3) reduce the heat source exposure to undesirable environments and potential launch pad accidents. An auxiliary cooling system must be operated until launch pad cooling is in operation and shall remain in a state of readiness as a back-up system.

Transfer of the Isotope Heat Source to the Launch Vehicle or Spacecraft mating level may be accomplished by the Mobile Launcher crane. A transfer mechanism may also be required to perform the horizontal or vertical installation on the spacecraft. These operations involving the heat source should be performed with controlled personnel accessibility and behind a light shield where feasible to minimize radiation exposure to support personnel. Controlled access and continuous monitoring of the area is required after the heat source is in place. Relatively low temperature ignitable materials and gases ($\sim 420^{\circ}K$) should be prevented from reaching the surface areas of the heat sources. The use of inert cover gases and purging is recommended.

The installation of small isotope heat sources is entirely feasible at the launch pad and is considered a safety advantage if accessibility permits. Adherence to radiological procedures, similar to those developed for the SNAP-27 fuel capsule (Reference 5-15) must be enforced.

5.2.5.3.3 Launch Pad Operations Safety Considerations

A summary of the key launch pad nuclear safety considerations is presented in Table 5-6.

Table 5-6. Guidelines for Operations on the Launch Pad

GENERAL

- Keep nuclear hardware operations at the launch pad to a minimum
- Consider mating and integration of nuclear hardware late in the launch pad timeline (just prior to loading of hypergolics and installation of ordnance is recommended)
- Limit and regulate personnel in nuclear hardware designated areas
- Provide personnel dosimetry, and permanent and portable radiation monitoring systems coupled with alarms and warnings
- Consider use of two man "buddy" system for work with nuclear hardware
- Provide and designate multiple escape routes for emergencies
- Provide nuclear hardware launch pad procedures in the KSC ground safety plan (K-V-053)
- No smoking or eating shall be allowed in designated nuclear areas

REACTOR

- Provide environmental protection of the power module during lift, mating and all operations at the service level of the ML (inert cover gas, purging, double containment, etc)
- Provide liquid metal leak detection capability
- Conduct thorough evaluation of the incompatibility of the present ML and pad fire protection system with liquid metals
- Provide special liquid metal fire protection and suppression techniques with the transporter and at the power module level of the ML
- Avoid use of materials, gases and liquids that are incompatible with liquid metal hardware

ISOTOPE

- Mate and integrate isotope hardware at the launch pad
- Provide redundant/back-up cooling capability during all operations
- Prevent low temperature (~420° K) ignitable materials and gases from approaching the radiating surfaces of the heat sources (consider cover gas & purging operations)
- Provide radiation and thermal shields for prolonged operations around a large isotope heat source

5.2.6 INDUSTRIAL SAFETY IMPACT AT KSC

The majority of nuclear hardware safety operations at KSC will not require procedures or personnel that are radically different from these already in use at KSC. The major areas requiring supplementation are radiological safety and fire prevention and suppression.

5.2.6.1 Radiological Safety

The radiological safety activity during prelaunch and launch can be categorized as routine handling and emergency handling. The routine handling of the nuclear hardware for a Space Base, including the reactor power modules should not require significantly different radiological safety procedures and support than those currently in use. The KSC document "SNAP 27 Radiological Control Plan" (Supplement II to Volume II of K-V-053 - Reference 5-15) provides an excellent guideline for the type of control and equipment that will be required. All activities associated with the handling and testing of nuclear hardware should make use of the two man "buddy system." Use of controlled access areas and personnel trained in the support of nuclear hardware operations, with a working knowledge of the hazards and characteristics of radiation is mandatory. Radiation safety personnel will be routinely concerned with 1) nuclear hardware criticality control and detection, 2) radiation control and monitoring, and 3) radiation contamination control and decontamination.

5.2.6.1.1 Criticality Control and Detection

Engineered safeguards, backed up by cross-trained personnel and strict adherence to procedures are required to prevent criticality of nuclear hardware due to packaging and stacking or inadvertent reactor excursions. Radiation monitors coupled with alarms must be provided to assist radiation safety personnel in planned evacuation of the area, in the event of abnormal

high radiation levels around the nuclear sources. The safety organization will be responsible for the identification of escape routes and monitoring the radiation exposures of the workers during these incidents.

5.2.6.1.2 Radiation Control

Radiation control procedures must follow routine Health Physics practices. These procedures include: the training of personnel, maintenance of individual exposure records, monitoring of log books, providing continuous and periodic health physics surveys and the establishment and control of limited access areas. The types of activities performed should include:

- Bioassays - Radiation workers must provide urine samples periodically and before and after each launch.
- Wipe Tests - Alpha wipe tests must be performed periodically and during and after major operations involving nuclear materials.
- Air Monitoring - Air samplers should continuously monitor the air in storage and test areas. Additional samplers should be located in the VAB and at the launch pad.
- Personnel Badge Monitoring - Film badges and self-reading dosimeters must be warn by radiation workers with results periodically recorded on personnel radiation exposure records.
- Radiation Surveys - Periodic gamma, beta and neutron radiation surveys must be made of the nuclear hardware. In addition, surveys are made during special operations (e.g., assembly transportation, etc.)
- Radiation Warnings - Proper warning signs on facilities and equipment must be installed and maintained.
- Radiation Control Zone Designation - Control zones must be established with regulation and controlled access to nuclear areas where personnel dosimetry is required.

The radiological safety procedures followed should be designed to insure that the radiation workers do not receive unnecesssary exposures or exposures in excess of those permitted under Federal Regulation 10CFR 20 (Reference 5-16), listed in Table 5-7. Dose guidelines for the general populace are specified in 10 CFR-100 and DML 50-268 (References 5-18,19)

and listed in Table 5-8. The general public should not be exposed to any radiation from the nuclear hardware under normal operating conditions. Since KSC is a restricted area and under NASA administrative control, all personnel could be considered "radiation workers," but this category should be limited to personnel assigned to work with or near the radiation sources, and therefore would be those who have access to the radiation control zones.

5.2.6.1.3 Contamination Control

Contamination control mainly consists of Health Physics surveys to insure integrity of the source cladding or containment vessels and controlling access and operations of personnel in contaminated areas. Isolation procedures must be developed and strictly followed in the event of a contamination accident. Eating, drinking and smoking must be prohibited to all personnel handling contaminated material or hardware until they have been monitored and found free of contamination. Proper respiratory equipment, anti-contamination and protective clothing must be readily accessible. Daily bio-assay samples must be evaluated and compared to permitted body burdens to prevent over-exposures.

5.2.6.2 Fire Protection

In general, potential fire hazards associated with the nuclear hardware arise from two sources: 1) the ignition potential presented by isotope heat sources and 2) the chemical reactions and subsequent combustibility of reactor power module liquid metals. Key to fire prevention in both instances is the provision of storage and work areas free of combustible or reactive materials, and the strict adherence to procedures and use of proper equipment. The launch vehicle propellants represents the largest source of combustible materials during the Prelaunch Phase. A discussion of the characteristics of launch vehicle propellant fires is contained in Appendix C of Volume III, Part 2.

5.2.6.2.1 Nuclear Fires

Reference is made to the Fire Fighting Plan developed for radioisotopes as listed in the KSC SNAP-27 Radiological Control Plan (Reference 5-15). The most important precautions to be taken by fire fighting personnel in nuclear radiation areas are to prevent inhalation

Table 5-7. Dose Limits for Ground Radiation Workers

Currently in Use (10 CFR 20)

Exposure	Condition	Dose (rem)
• Whole Body - Head, trunk active blood-forming organs, gonads, lens of eye	Accumulated Quarterly	5 (N-18 yr) 1.25
• Skin - of whole body	Year Quarterly	30.00 7.50
• Hands - and forearms, feet and ankles	Year Quarterly	75.00 18 75

Recommended (NCRP-39) Jan. 15, 1971 (Ref 5-17)

Exposure	Condition	Dose (rem)
• Whole Body	Long term Accumulated	5(N-18 yr) 5/year
• Skin	Year	15
• Hands, feet and ankles	Year Quarterly	75 25
• Forearms	Year Quarterly	30 10
• Other Organs	Year Quarterly	15 5

Table 5-8. Dose Guidelines for General Populace

Permitted Exposure Standards (10 CFR 20)

Exposure	Dose Rate (rem/period)
• Whole Body	0.002/hour 0.100/week 0.500/year

Accident Exposure Guidelines

Exposure	Dose (rem)
External	
• Whole Body	25*
Internal	
• 70 Year Bone Dose	150**
• Thyroid	300**
• Lower Large Intestine	75**
	*10 CFR-100 **DML50-268

or ingestion of toxic particles and to avoid contamination of their bodies and equipment. Fighting a plutonium fire is similar to fighting any toxic propellant: Personnel must wear anti-contamination clothing and respiratory protection.

The use of significant amounts of water around a Zr-H reactor should be avoided because water acts as a neutron moderator and therefore increases the criticality potential. Facility design should minimize the potential for free standing water where a reactor could be partially or completely immersed.

5.2.6.2.2 Liquid Metal Fires

Alkali (liquid) metals contained in a reactor power module, such as NaK, require special considerations in safety and fire protection because of the high degree of reactivity liquid metals have with many common substances. The reaction products themselves pose a problem as they are irritants, they may be highly corrosive, and may then lead to fires and explosions, unless properly controlled.

While it is true that liquid metals possess many properties which make them hazardous for certain applications, proper precautions permit their safe use even at high temperatures and pressures. Detailed procedures in the handling and associated fire control of liquid metals are available in numerous references (e.g., References 5-5, 5-20, and 5-21). In addition, the Liquid Metal Engineering Center operated for the U.S. Atomic Energy Commission by Atomics International is available for consultation and as a source of reference material.

These sources of information should be used extensively in the detailed planning of facilities and development of procedures to handle the liquid metals involved in the reactor power modules. A discussion of the reactive characteristics of liquid metal and some of the safety precautions which should be taken are presented in the following paragraphs.

The prelaunch environment presents some obvious hazards. Significant quantities of substances which react with NaK are commonly used as fire suppressants, cleaning solutions

and launch vehicle propellants, two of the most common being water and oxygen. In addition, the relatively high humidity of the Florida environment adds to the danger.

When liquid NaK (melting point ~ 260°K) and water are brought into contact with each other a vigorous exothermic chemical reaction takes place. Sodium and potassium oxides are formed and heat and hydrogen are liberated. If the reaction occurs in air, ignition of the liberated hydrogen and oxygen from the air can occur. If sufficient water and oxygen are present the reaction may be explosive and damage to equipment may occur as a result of physical and thermal effects and fire.

Even small quantities of NaK can be hazardous when mixed with water. An uncontrolled reaction between quantities as small as several Kilograms of reactants in a room or enclosed area can completely disrupt the facility and severely damage an entire conventional building.

The reactions of liquid metal with air may not be as immediate as they are with water, but NaK will generally ignite spontaneously in air, and combustion will be sustained if initial conditions of temperature and environment prevail. Upon ignition, the temperature of the burning mass increases rapidly to 1150°K (1600°F) and it continues to burn, giving off large quantities of opaque, white smoke making visibility very poor. No flame is visible but only a glowing mass of the metal. Fumes resulting from combustion are hazardous and protective equipment must be worn by personnel combating NaK fires.

Fires are generally extinguished by the removal of oxygen. Extinguishing materials normally used must not be applied to liquid metal fires because of the reaction with common extinguishers containing O_2, such as water, carbon tetrachloride, carbon dioxide and sodium bicarbonate. The exclusion of oxygen can be effected by covering the burning metal with such materials as dry alkali metal chlorides, graphite, or soda ash (calcium carbonate). Met-L-X dry powder is an impregnated sodium chloride which is free flowing and not susceptible to moisture pickup. Another commercial material is Pyrene G-1 powder, a graphite-base material.

Yellow is the adopted color for liquid metal fire protection equipment. Extinguishers, buckets, bottles, tubes and shovels used for this purpose should be painted yellow for easy identification.

Complete coverage of the burning area and material is essential. Fires on vertical or irregular surfaces pose a problem because of the difficulty in application of the extinguisher. A possible solution to this problem is the provision of a steel sump or sink whereby the metal can be dumped and concentrated in one place and then covered with extinguisher. The power-module radiator coolant loops do not lend themselves to this provision. An inert cover gas environment (double containment) combined with proper extinguishers and procedures are the solution.

Disposal and clean-up can be as hazardous an operation as the fire fighting itself. On the other hand, it is a relatively safe operation if adequate personnel protection is used and proper precautions are observed.

As can be determined from the above material, the fire protection provisions at KSC are presently incapable of supporting a reactor power module. In addition, known incompatibilities of presently used substances with liquid metals exist. The effective control and prompt extinguishment of liquid metal fires at KSC can be accomplished through implementation of a program which includes special design considerations as well as careful adherence to procedures, use of trained personnel and provision of proper equipment. In order to implement such a program, a thorough study is recommended with emphasis on the VAB and launch pad. The following general considerations are provided in Table 5-9 and should be followed in any liquid metal fire protection program:

Table 5-9. Guidelines for Liquid Metal Fire Protection Operations

1	Remove potential reactive materials from the vicinity of the liquid metals
2	Provide proper and adequate personnel protection equipment • Clothing • Respiratory equipment • First aid
3	Provide liquid metal fire fighting equipment and extinguishing agents The equipment and containers must be marked yellow
4	Provide well trained personnel with considerable actual liquid metal fire-fighting practice
5	Extinguishing agents should be applied carefully to prevent splashing
6	Complete coverage of the fire is mandatory (apply at blanket)
7	Consider use of sump tanks to remove remaining metal safely
8	Never apply normal fire extinguishants containing water or oxygen
9	Consider controlled environments utilizing inert gases and double containment when unable to remove nearby reactive materials
10	Adherence to all regulations and procedures is mandatory
11	Provide nuclear and liquid metal facility design to prevent the presence of moisture and standing water

5.2.7 FACILITY IMPACT

Considerable use can be made of existing KSC facilities (Reference 5-14) in supporting the prelaunch operations of the nuclear hardware. The major components at the Launch Center include: The Vehicle Assembly Building (VAB), where the launch vehicle and payloads are assembled and tested; the Launch Control Center (LCC) which provides the display, monitoring and control equipment for prelaunch and launch operations; the Mobile Launcher (ML) which in conjunction with the Crawler-transporter provides the launch platform and principle environmental and umbilical support in the VAB and at the pad. The Crawler-transporter travels some 8 km on a specially prepared roadway to deliver the Mobile Launcher and the launch vehicle/payload to the launch pad.

KSC facility requirements must be based on future program requirements. In instances, where several power modules and isotope heat sources must be accommodated, modifications to existing facilities and new specialized facilities are required to ensure the safety of the operations. Special facilities recommended for KSC include an isolated nuclear assembly storage, assembly

and checkout building as well as liquid metal servicing facilities capable of supporting three reactor power modules in addition to several isotope heat sources. Nuclear hardware fire protection, environmental protection, handling and servicing modifications are required in existing facilities (eg Vehicle Assembly Building, Mobile Launcher, Launch Pad). In the examples identified the Mobile Launcher is a common and possibly a prime facility.

Table 5-10 identifies the major facility usage requirements at KSC in support of reactor power module and isotope heat source nuclear hardware.

5.2.7.1 Existing Facilities and Operations

The principal existing facility modifications required are:

- Support and Service Structures
- Environmental Control
- Fire Protection
- Radiological Control

The nuclear hardware configurations and power module dimensions are not firm and therefore it is unreasonable to affix firm specifications on the support hardware at this time. The intent is to identify where modifications can be expected for nuclear hardware typical of a Space Base Mission.

Support & Service Structures - Minor modifications in the service arms of the Mobile Launcher (ML) and access platforms of the VAB can be expected. The most significant impact is on the ML crane if future requirements call for the integration and matting of the nuclear hardware at the Launch Pad.

The mass of a completely assembled nuclear power module ($\sim$30t) will exceed the design capacity of the ML crane (22.7t at 15m, 9t at 26m extension from center of tower). Adequate clearance must be maintained from the tower center line to account for wind loading. Modular design of the nuclear hardware would reduce crane capacity requirements.

Table 5-10. Facility Impact Summary

	Potential Use	Facility Modifications	Nuclear Hardware Considerations
EXISTING FACILITIES			
Mobile Launcher (ML)	Assembly and launch platform, launch checkout, crane, environmental cover gas, umbilical connections, thermal control, catwalk access, fire protection, controlled access.	• Possible service arm mods • Environmental cover gas capability • Thermal Control (Isotope) • Fire protection equipment • Radiation monitors • Crane (possible)	• Environmental Shroud • Fragmentation Shielding • Thermal Control (Isotope) • NaK Leak Detection (Reactor) • Escape/Ejection (Isotope) • Modular design
Launch Site/Pad	Launch pad, gas compressor facilities, umbilical connections, fire protection, data link terminals Personnel excape provisions	• Fire protection and pad water	
Vehicle Assembly Building (VAB) (High Bay)	Assembly and installation, prelaunch checkout, protected environment, fire protection, service crane, controlled access	• Access platforms • Emergency Control • Fire protection • Radiation monitoring	• Payload simulator • Thermal Control (Isotope) • NaK Leak Detection (Reactor)
Launch Control Center (LCC)	Monitoring and control of prelaunch and launch activities, instrumentation, data collection	• Instrumentation and monitoring	
Ordnance Storage Area	Test and storage of nuclear hardware ordnance such as disposal rocket motors, ingiters and squibs	• Minor if any	• Separable Disposal Rockets, igniters and squibs
Mobile Service Structure (MSS)	Potential use in the installation of ordnance, access platforms	• Minor if any	
Converter Compressor Facility	Supply of Nitrogen, Helium or Argon cover gas	• Possible Argon capability (if used)	
Fire Alarm and Protection System	Notification and location of existing fires	• Liquid metal fire detection	• Sensors
Area Warning System	Warning and control in hazardous areas - VAB, ML, NAB Liquid Metal Facility, Launch Pad	• Nuclear hazards • Radiation monitoring	• Sensors
Barge Terminal or Skid Strip	Receipt of nuclear hardware and unloading, radiation monitoring	• Radiation Monitoring	• Protective, and conveniently handled containers
Radiation Control and Medical Treatment	Radiation control of personnel, badge processing, urine	• Expanded capability	
ADDITIONAL FACILITIES			
Nuclear Assembly Building (NAB)	Receipt, inspection, assembly, checkout and storage of nuclear hardware. Isolation from industrial area, launch pads and VAB. Railroad spur.	• Thorough review of existing facilities should be made prior to authorization for new facility.	• Minimum checkout at KSC • NaK Leak Detection (Reactor) • Thermal Control • Interface hardware
Liquid Metal Servicing Facility (LMSF)	Initial servicing, unloading and cleaning capability	• Consider limited facility capable of expansion to provide complete charging, repair and unloading of NaK	NaK completely loaded at factory

Environmental Control - An inert cover gas of Argon, Nitrogen or Helium is required of Reactor Power Modules whenever possible. Cover gas and purge supplies would be required on the ML, within the VAB and at the Launch Pad. Portable unit should be available during transportation and these units would be combined with permanent facilities on the ML or in storage and assembly areas within the NAB to provide back-up capability.

Isotope heat sources generally require dry air or nitrogen cooling. Backup systems must be provided. The portable units used for transportation can provide the backup capability at the Launch Pad. The primary N_2 source should be supplied at the isotope heat source level on the ML.

Fire Protection - As has been stated in Section 5.2.6.2, fire protection must be provided at all facilities. The nuclear reactor moderating potential and liquid metal reaction caused by water and other commonly used substances presents an incompatibility with normal currently-in-use fire protection procedures. A thorough study of this problem is recommended, particularly at the Launch Pad and in the VAB.

Radiological Control - The radiological control program currently utilized for the SNAP-27 power system (Reference 5-15) can be implemented and expanded where necessary to provide for the additional facilities and operations involved with the launch of a reactor power module. The primary purpose of radiological contol is to (1) provide the detailed procedures to ensure no unnecessary exposure of personnel during the mission and (2) provide the ability to cope with all conceivable accidents effectively and with minimum harazrd to personnel.

Accident effects involving nuclear hardware can be minimized by (1) providing protective measures and contingency plans for immediate vicinity personnel, (2) quick execution of safing and contamination control procedures, and (3) escape mechanisms for jettison of hardware away from severe environments.

Nuclear accidents requiring emergency procedures and extensive contamination control are remote. Plans for exercising prompt and effective control of the situation and the location of

nuclear facilities away and downwind of populated areas will further minimize the potential hazard. Multiple escape routes, respiratory equipment and protective clothing must be provided in work areas.

Plans and techniques for protection and safing of a reactor and isotope systems during a launch pad abort should be developed. A discussion of this problem is contained in Section 5.3. It does not appear desirable to provide a launch escape or jettison system for a reactor power-module assuming the fission product inventory is minimum due to the limited pre-operational criticality tests. This same conclusion does not necessarily apply to all isotope systems. Since relatively large isotope inventories exist during prelaunch. The design of a reactor shield should provide protection from the fragmentation, explosion and fire environments of a launch pad accident.

Decontamination procedures after an accident will be of the same type as those contained in Reference 5-15. A three phase decontamination procedure has been identified:

1) Gross decontamination
2) Removal of non-fixed particulate contamination
3) Removal of fixed particulate contamination

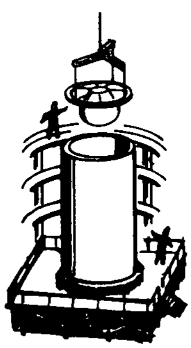
The first phase consists of a trained team to identify the extent of contamination, locate contaminate areas, control access and remove major contaminated parts. The second phase will consist of a thorough cleaning and disposal of all removable contamination. Areas and items with non-removable contamination will be left for the third phase where concrete is chipped out, steel cut and chemicals, sandblasting or steam is used for complete cleaning. Repainting surfaces is sometimes permissible where the external radiation level of isotopes such as Pu-238 is nearly zero. Appendix H of Reference 5-15 contains additional guidelines for radiological decontamination.

5.2.7.2 Nuclear Assembly Building

The majority of the nuclear hardware prelaunch activities should be accomplished in an isolated facility capable of supporting assembly, testing and storage operations. Existing facilities at facilities at KSC such as the Pyrotechnic Installation Building located in the Industrial Area may meet future requirements of a single reactor power module. However, this facility is inadequate for processing and storage of several reactor power module and isotope heat sources.

A new facility, hereafter referred to as the Nuclear Assembly Building (NAB) is required at KSC for a program involving several large nuclear sources (eg: Space Base). The NAB should be capable of supporting a minimum of three nuclear reactor power modules and several isotope heat sources in various stages of assembly, test and storage. Reactor and isotope storage must be separated from the assembly and test bays by suitable radiation shielded, blastproof and fireproof walls.

Present plans require the handling of an entire power module assembly in a horizontal position. However, this technique may require complex GSE and handling operations in order to provide safe horizontal support of the heavy reactor/shield within the module. If vertical assembly and test were planned, a recessed pit should be considered (Figure 5-14).



VERTICAL ASSEMBLY

Figure 5-14. Vertical Assembly in VAB

The requirements and hazardous characteristics of reactor power modules differ significantly from those of an isotope heat source. A low nuclear and liquid metal hazard potential and low radiation exposures to personnel can be achieved by providing separate assembly areas for isotopes and reactor power modules where simultaneous operations can be performed.

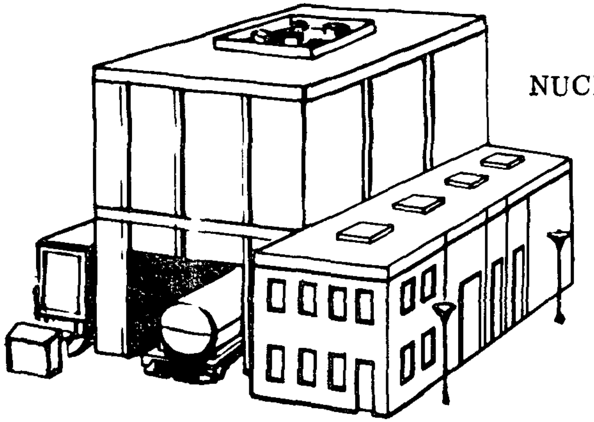
A typical layout of such a facility and preliminary requirements are shown in Figure 5-15. A railroad spur is shown adjacent to the building to provide transportation and potential storage capability for isotope heat source fuel capsules within the ATMX Series 500 railcar.

The area requirements of the NAB could be substantially changed depending on multiple program usage. Reactor power module requirements of future unmanned programs have not been included although it is expected these programs would utilize this facility. The use of an isotope-Brayton system could increase the isotope storage requirements.

Location of the NAB requires relative proximity to the railroad, road, the VAB and Launch Complex, yet provide sufficient isolation from normally populated areas. A suggested location is shown in Figure 5-16.

Nuclear and fire safety precautions must be provided to protect workers, hardware and the surrounding environment. Radiation protection requirements can be met by providing shielded and isolated work and storage areas equipped with radiation detection monitoring, and alarm instrumentation. Multiple access and escape routes must be planned.

Minimizing moisture within the NAB should be a design objective. The building should be waterproof and there should be no sprinkler system, exposed water pipes or steam lines in the work and storage areas. The floor should be sealed concrete and sufficiently elevated to prevent water from entering. Continuously operating power ventilators with proper filtering should be provided to remove moisture. Smoking, eating and open flames should be prohibited in most areas. Switches, lights and motors must be explosion and arc proof. Cover gases should be maintained when possible to further reduce any possible reactivity and exposure to the atmosphere.



NUCLEAR ASSEMBLY BUILDING

PRELIMINARY REQUIREMENTS

High Bay Area #1 (Prime EPS C/O & Vertical Stacking)

Area	590m^2 (6350 ft^2)
Height (vertical stacking)	22m (72 ft)
(horizontal)	13m (45 ft)
Crane Capacity	46t (100Klb)
Door Size	12m Wide x 12m High

High Bay Area #2 (Prime Isotope System C/O & Secondary EPS Area)

Area	440m^2 (4750 ft^2)
Height	12m (40 ft)
Crane Capacity	46t (100Klb)
Door Size	12m Wide x 11m High

Storage Area #1 (2 Bays for EPS)

Area	330m^2 (3600 ft^2)
Height	9.2m (30 ft)

Storage Area #2 (Isotope Storage)

Area	340m^2 (3650 ft^2)
Height	7m (23 ft)

Additional Requirements

- Office Space
- Environmental Control & Air Filtration System
- Helium-Zenon Servicing
- Inert Cover Gas Service (Argon, He, or N_2)
- Isotope Cooling
- Railroad Spur
- Controlled Access
- Multiple Escape Provisions
- Radiation alarm & detection system
- Fire Protection
- Liquid Metal Leak Detection

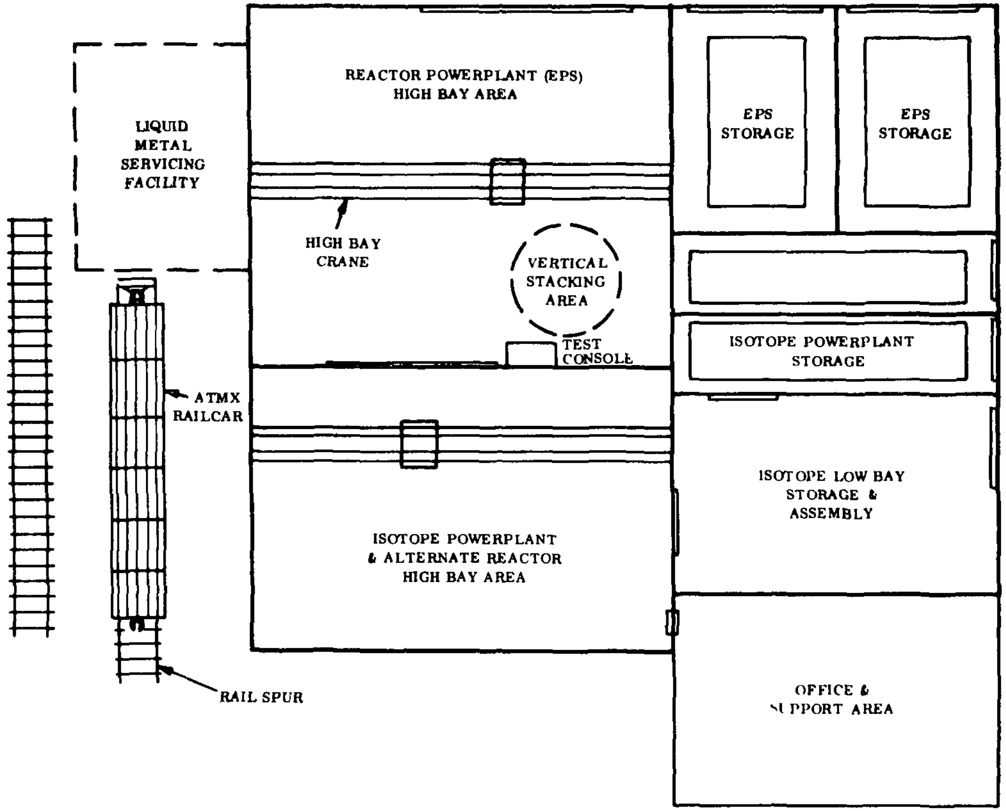


Figure 5-15. Nuclear Assembly and Storage Building

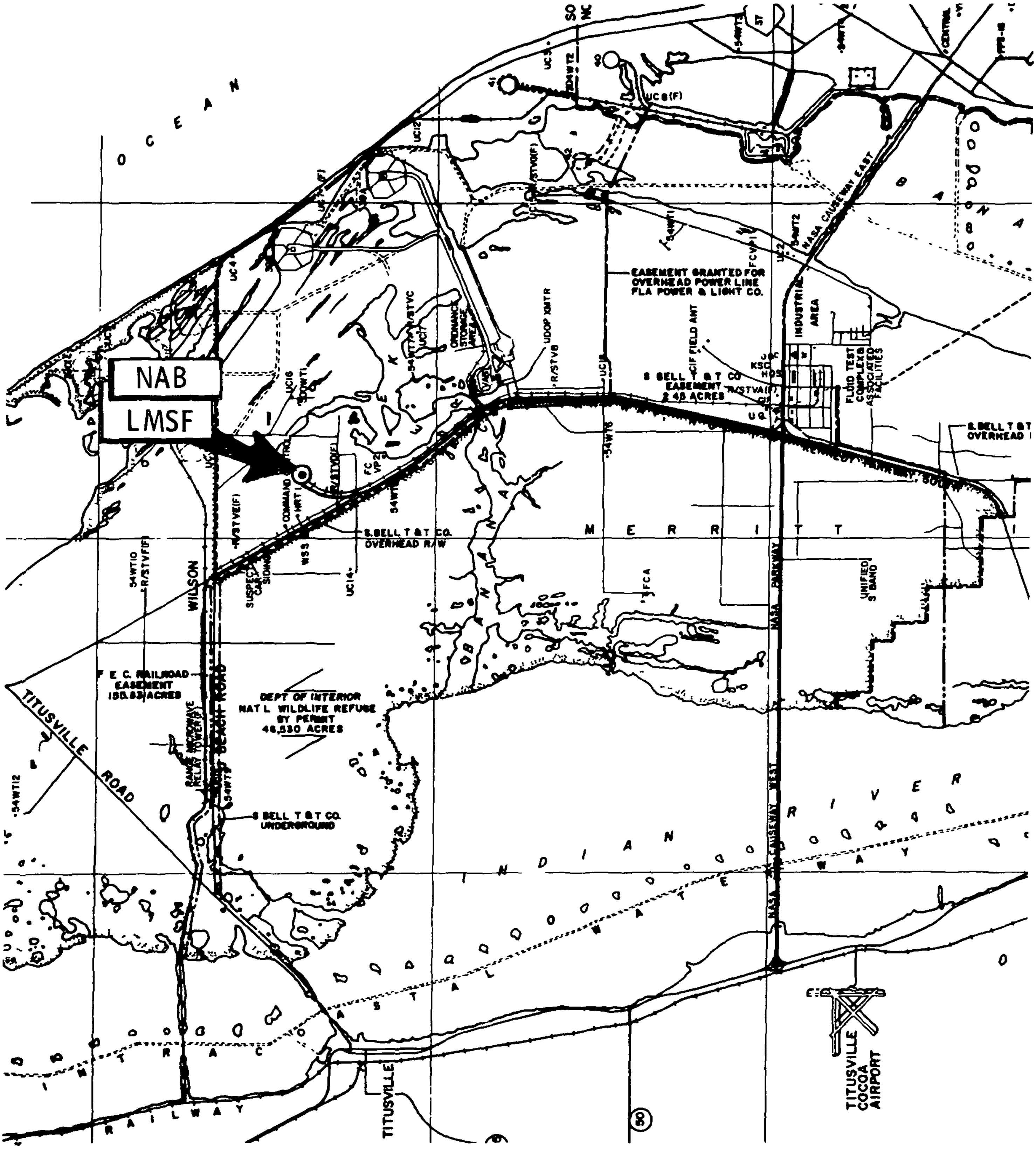


Figure 5-16. NAB Suggested Location

5.2.7.3 Liquid Metal Servicing Facility

The reactor power modules would be shipped direct from the factory with a full complement of NaK. NaK loops would remain filled and unopened throughout the remaining portion of the mission. This procedure eliminates the need for extensive liquid metal processing and charging facilities at KSC, but a limited servicing capability is still required to perform safing operations if liquid metal leaks or line ruptures should occur. After safing and cleanup and power-module would be shipped back to the factory for repair.

This mode of operation appears to be appropriate for limited nuclear operations at KSC. However, a full capability liquid metal servicing facility should be considered when future multiple mission requirements dictate.

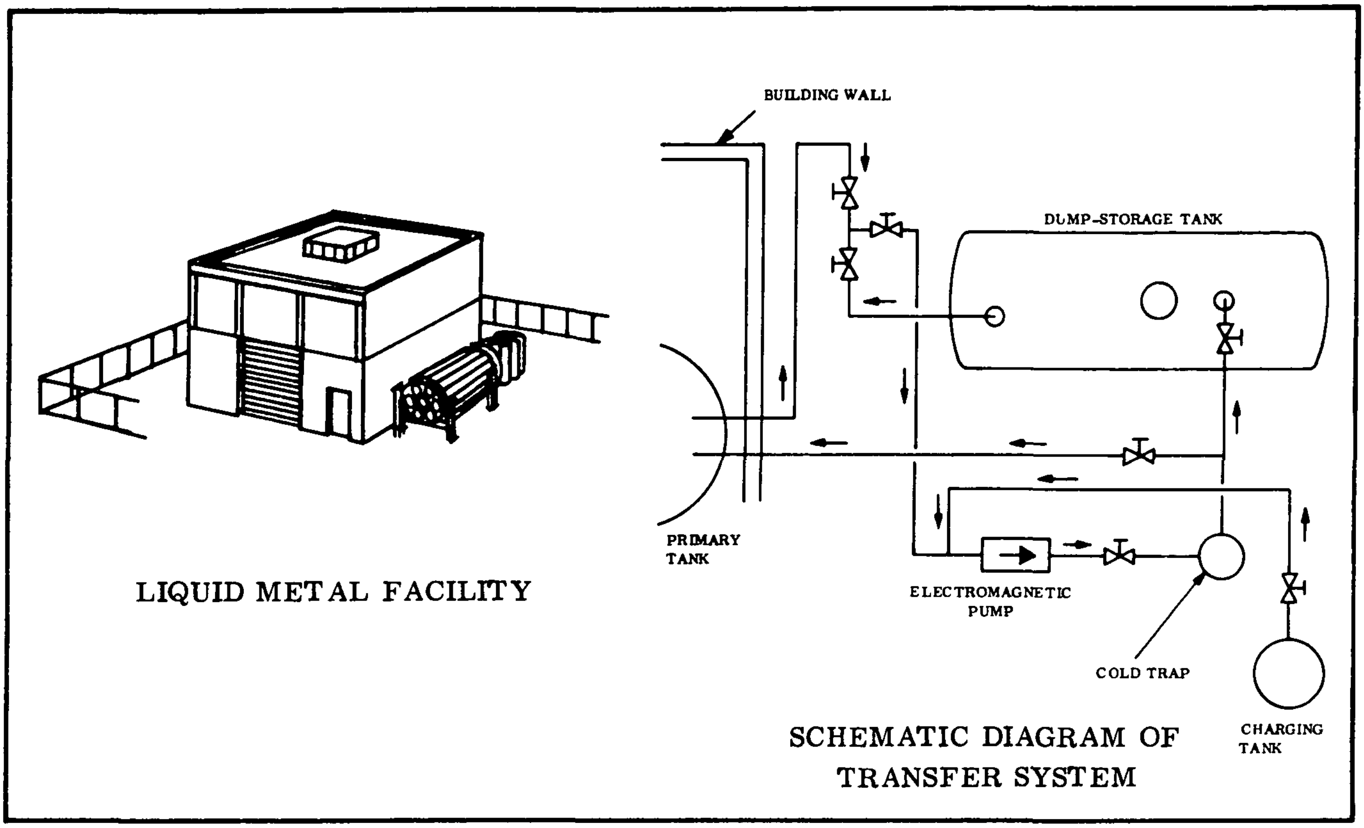
The Liquid Metal Servicing Facility depicted in Figure 5-17 is typical of the limited facility which would be required, which is capable of expansion as requirements dictate. The preferred location is approximately 100m from the NAB but within the same perimeter fence. An alternate location, providing greater accessibility, would be immediately adjacent to the NAB separated by fireproof walls.

The prime considerations in the safe operation and design of the facility are the provisions for complete isolation from moisture and reactant substances along with proper fire protection. Liquid metal containers must be raised off the floor on blocks or grates to allow visual checks for leaks and corrosion. Drip pans are also required to catch and keep dripping metal off the concrete floor. Cover gases (Helium, Nitrogen, Argon) should also be considered.

In all operations involving the use of liquid metals and nuclear hardware, it is vitally important that cleanliness be maintained, that proper clothing is worn and "buddy system" rules are rigidly enforced.

5.3 LAUNCH/ASCENT NUCLEAR SAFETY

The Launch/Ascent Phase begins with ignition of the S-IC stage followed by lift-off of the booster and terminates with the successful completion of rendezvous and docking of the nuclear



INITIAL FACILITY PROVISIONS

- FIRE PROTECTION
- PERSONNEL PROTECTION
- COVER GAS SUPPLY
- COVER GAS SAMPLING
- GAS PURIFICATION
- NaK BULK STORAGE
- LEAK TESTING
- PURGING
- EVACUATING/UNLOADING
- MINOR MAINTENANCE
- POST OPERATIVE CLEANING
- WASTE DISPOSAL

COMPLETE FACILITY PROVISIONS

- FIRE PROTECTION
- PERSONNEL PROTECTION
- COVER GAS SUPPLY
- COVER GAS SAMPLING
- GAS PURIFICATION
- LEAK TESTING
- PURGING
- EVACUATING/UNLOADING
- POST OPERATIVE CLEANING
- WASTE DISPOSAL

* BULK & TANK CAR STORAGE OF LIQUID METALS
* MATERIAL EXPOSURE FACILITIES
* LIQUID METAL SAMPLING
* LIQUID METAL PURIFICATION
* CHARGING SYSTEM
* SUPPLY SYSTEM
* MAJOR MAINTENANCE

*ADDITIONAL PROVISIONS

Figure 5-17. Liquid Metal Servicing Facility

payload. A typical launch/ascent flow plan is presented in Figure 5-18. For purposes of this study, it is assumed that an S-II kick-stage is used to perform final rendezvous. Actual docking is initiated by the Space Tug. Replacement powermodule components and isotopes are assumed to be transported by the Space Shuttle.

The principal mission support interfaces of the Launch/Ascent Phase are identified in Table 5-11.

Table 5-11. Potential Nuclear Hardware Interfaces During Launch Ascent

NUCLEAR HARDWARE/RELATED OPERATIONS \ POTENTIAL INTERFACES	MOBILE LAUNCHER	SERVICE ARMS	LAUNCH PAD GSE	LCC	RANGE SAFETY	MCC	TELEMETRY SYSTEMS	CAMERA PADS	S-IC	S-II	KICK STAGE	IU	SHROUD	KSC PROPERTY	SHALLOW WATER AREAS & BURN PONDS	CONTINENTAL SHELF	DEEP OCEAN	RECOVERY CREWS	EURASIAN CONTINENT	SPACE TUG	FLIGHT CREW-SPACE TUB/BASE	SPACE BASE/STATION (SEPARATE LAUNCH)
S-IC IGNITION	⊗	⊗	⊗	⊗	⊗		⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗			⊗				
LIFT-OFF	⊗	⊗	⊗	⊗	⊗		⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗			⊗				
S-IC BOOST				⊗	⊗		⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗				
S-IC TERMINATION				⊗	⊗		⊗	⊗	⊗	⊗	⊗	⊗	⊗			⊗	⊗	⊗				
STAGE SEPARATION				⊗	⊗		⊗	⊗	⊗	⊗	⊗	⊗	⊗			⊗	⊗	⊗				
S-II BOOST				⊗	⊗		⊗	⊗		⊗	⊗	⊗	⊗			⊗	⊗	⊗	⊗			
S-II CUT-OFF & SEPARATION				⊗	⊗	⊗	⊗			⊗	⊗	⊗	⊗			⊗	⊗	⊗	⊗			
COAST						⊗	⊗				⊗		⊗									
S-II KICK STAGE BOOST						⊗	⊗				⊗		⊗									
SHROUD JETTISON						⊗	⊗				⊗		⊗									
COAST						⊗	⊗				⊗											
SPACE TUG RENDEZVOUS & DOCK						⊗	⊗				⊗									⊗	⊗	
KICK STAGE SEPARATION						⊗	⊗				⊗									⊗	⊗	
RENDEZVOUS & DOCK TO BASE						⊗	⊗													⊗	⊗	⊗

× REACTOR POWER MODULES

○ ISOTOPE SYSTEMS

⊗ BOTH

5.3.1 RADIATION HAZARDS

The potential radiation hazards during the Launch/Ascent Phase result principally from mission aborts and accidents which cause the nuclear payloads to impact land or water at some point along or near the trajectory trace, creating a potential hazard to personnel and the ecology. The radiation hazards from the reactor power modules or Isotope systems are in the form of direct radiation or the release of fission products to the ecological system which in turn are directly or indirectly assimilated through the process of inhalation or ingestion. A thorough discussion

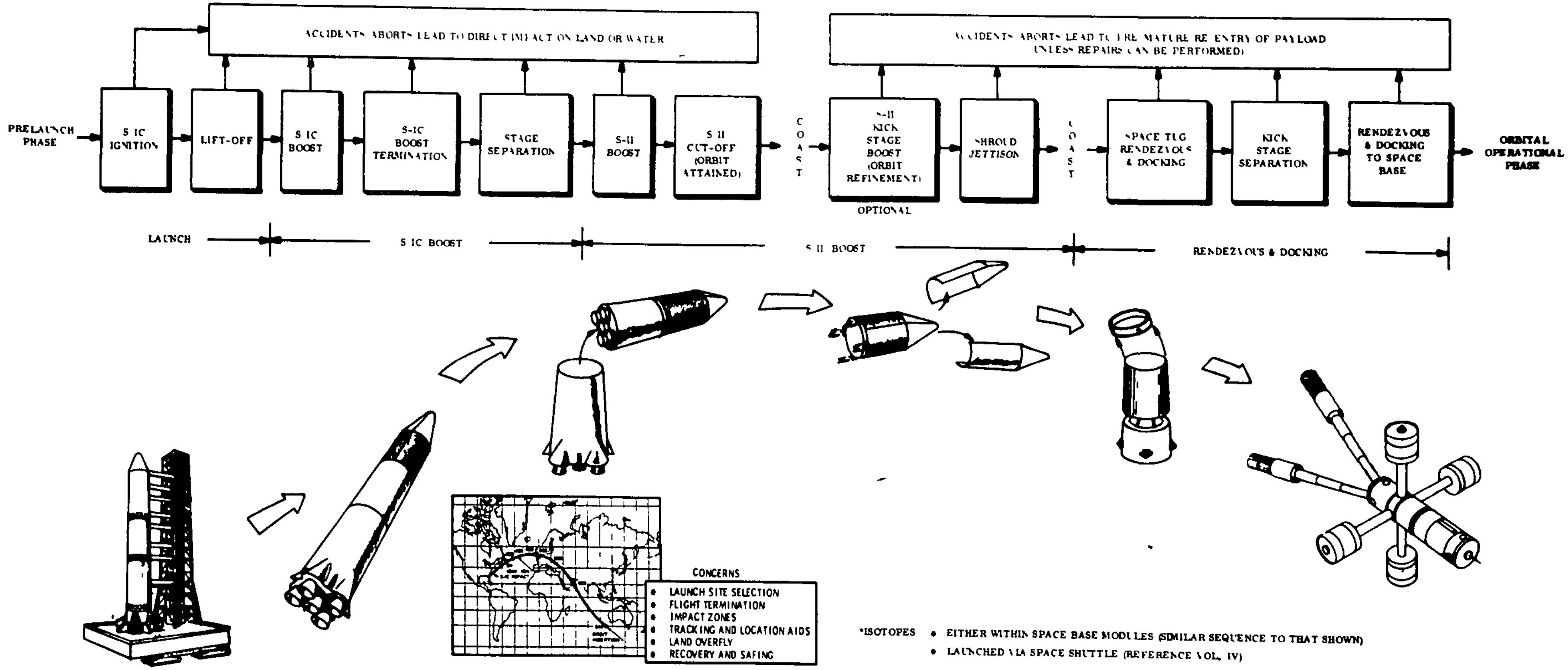


Figure 5-18. Launch/Ascent Flow Plan (*Nuclear Payloads)

of the accident causes and consequences arising from the reactor power modules during the Launch/Ascent Phase is presented in Volume III and Volume IV Part 2 of this study. The po potential hazards and consequences of typical isotope payloads which may be flown can be obtained from References 5-8, 5-22, 5-23 and Volume IV Part 2 of this study.

The liquid metal hazard was treated quite extensively during prelaunch. It is not considered a significant hazard during launch and ascent phase as the propulsion stages have considerably greater energy release potential. However compliance with Range Safety Requirements pertaining to toxic and combustible material must be maintained.

The key mission support functions required to provide maximum nuclear safety of the mission through the Launc/Ascent Phase are:

- Range Safety
- Radiological Control
- Mission Control

Each are briefly discussed in the following paragraphs.

5.3.2 RANGE SAFETY

The Eastern Test Range (ETR) provides many of the facilities and instrumentation systems to support the launch and ascent operations through the injection of the payload into earth orbit. Every reasonable precaution must be taken to minimize the risk to life, health and the ecology. The responsibility for safety during launch is given to the Range Missile Control Division and the Safety Office. Reference is made to the "USAF Range Safety Manual" (Ref. 5-24) for the present modus operandi.

The following paragraphs contain some of the key Range Safety considerations in the launch of nuclear hardware typified by a Space Base Mission.

5.3.2.1 Launch Site Selection

The location of the Complex 39 launch pads at KSC are ideally situated for easterly launches of nuclear payloads. The pads are relatively isolated from large population areas and permit launch directly over open ocean areas. The single major undesirable feature is the presence of large amounts of shallow water which is conducive to reactor quasi-steady state operation should an impact occur in that area. A controlled area with a radius of approximately 13 km (8 nm) has been specified and appears adequate for the preparation and launch of nuclear material at KSC. The controlled area is defined as that area in which all personnel are under direct administrative control. The 13 km radius from the perimeter of nuclear facilities located near the VAB remains within the boundaries of KSC and the ETR.

Launches of nuclear hardware should be scheduled with prevailing winds from a westerly direction (blowing away from populated areas). This guideline is not necessarily a mandatory requirement for the launch of a reactor, but should be rigidly followed in the launch of an isotope power system. The toxic nature of the liquid metal on-board the reactor should also be given consideration in the application of this guideline.

Polar launches over central and Southern Florida and Cuba are not permissible with nuclear payloads. This guideline is presently being followed by NASA and the Air Force Eastern Test Range.

5.3.2.2 Flight Termination and Trajectory Implications

No nuclear payload should be intentionally jettisoned or impacted on land. Proposed flights will normally not be approved by Range Safety if normal impact dispersion areas for such items encompass land (Ref. 5-24). In the event of inadvertant land impact, a trained impact recovery team in conjunction with a Radiological Safety officer must assess the situation, obtain radiological measurements and take the necessary steps required to control and render the area safe (Refer to Section 5.3.3).

The established flight termination impact area Instantaneous Impact Predictions (IIP's) for reactor and isotope hardware should be restricted to outside the continental shelf. It has been

determined (Ref. Volume III) that the reactor presents no credible hazard in deep ocean areas. Other studies (Ref. 5-8) indicate this to be generally true for isotopes as well. Obviously erratic flight and other conditions may prevail where it may be required to initiate termination inside the impact limit lines. Control of the aréa, safing and possible recovery must then be initiated.

The reference 55^{o} inclination orbit with a 46^{o} launch aximuth requires an overfly of the Eurasian continent. The radiological safety implications and consequences of this trajectory are presented in Volume III, Part 3 of this study and in Ref 5-8.

Premature flight termination of the S1II stage can cause IIP's within the continent. Although it has been concluded that the radiological risks of a "clean" reactor power module are relatively low, a southerly launch should be given strong consideration. This trajectory would require a dogleg maneuver. Nonetheless, if payload margins permit, the southerly route is recommended.

5.3.2.3 Destruct Systems

The launch of nuclear materials necessitates a new look at range safety procedures, particularly in regard to destruct options.

Current requirements (Ref 5-24) specify that all primary launch or propulsion vehicles must contain two independent command flight termination systems. If certain thrust stages (Space Tug, Disposal System) are injected into orbit prior to their ignition, command systems are not required for these stages. Command destruct systems must however be installed on the powered stages (S-IC and S-II) capable of destruction of the lower as well as the injected stages by means of installed destructors. Several modifications to this procedure should be considered.

The S-II destruct system should be safed before Eurasian land mass overfly in order to take advantage of any possible range extension. Before destruct command, a signal would be sent for engine cut-off which then arms the destruct system. The range safety officer must assess several data points before reaching the decision to destruct. Typical reaction time for a range safety officer to initiate the destruct command is 20 seconds.

Due to the rather severe explosive and fragmentation environment caused by a booster destruct, consideration should be made for jettison of the nuclear package moments before destruct initiation. The desirability of separation prior to destruct is however, questionable. Timing is critical and large ΔV's are required. The effects of such a destruct delay on range safety must be carefully evaluated. Other alternatives to this procedure include the incorporation of a fragmentation shield around the nuclear hardware or rather extensive launch escape systems such as that employed on the Apollo Spacecraft.

5.3.2.4 Tracking and Location Aids

The incorporation of tracking and location aids such as beacons, pingers and dye markers will assist in the location of nuclear devices and reduce potential hazards to the populace and general ecology. These aids should provide (1) immediate tracking data for ground radar and trackers and (2) delayed location assistance for impact in water or on land. Tracking and location hardware must be compatible with Range instrumentation and recovery force equipment. Similar equipment will assist in the end of mission and recovery phase of the mission (Section 5.5). Flotation gear has been given consideration for recovery of large isotope systems. A timed or transmitted signal could initiate a scuttle if location and recovery could not be completed.

A summary of the key Range Safety considerations are presented in Table 5-12.

Table 5-12. Guidelines for Range Safety Operations

1	An administratively controlled area with a radius of approximately 13 km should be maintained in the selection of sites and performance of nuclear activities
2	An exclusion area of approximately 4 km radius should be maintained from the launch site during the launch
3	Launches of nuclear hardware at KSC should be scheduled with prevailing winds blowing away from populated areas (out to sea)
4	Polar launches over Central and Southern Florida and Cuba are not permissible with nuclear payloads
5	Consider a southerly launch azimuth to avoid the Eurasian overfly of the S–II and payload for the 55° inclination orbit
6	Flight termination impact areas should be outside the continental shelf
7	Consider command destruct delays to allow separation of the nuclear payload prior to stage destruct
8	Consider safing the S–II destruct system as Eurasian overfly is made
9	Provide tracking and location aids for land and water recovery
10	Provide trained impact and recovery teams for quick location and safing of contaminated areas
11	Conform to requirements of the USAF Range Safety Manual and provide necessary modification inputs
12	Consider use of floatation gear for large isotope systems

5.3.3 RADIOLOGICAL CONTROL

Radiological control during the Launch/Ascent Phase is most effectively administered by (1) the establishment and rigid control of an exclusion area around the launch site and (2) the prompt use of impact/recovery teams.

An exclusion area should be established during launch, with a radius of approximately 4 km. Only the necessary impact/recovery teams would be allowed. This procedure is essentially the same as the present fallback area in current use by KSC for an Apollo Saturn V launch from Complex 39.

Upon an abort and subsequent impact of nuclear hardware in the vicinity of the launch complex, the team would be dispatched and obtain a radiological assessment as discussed in Section 5.2.7.1. Prompt location and enforcement of controlled access areas is essential. Cleanup and decontamination will then be initiated. Specially designed handling tools will be required for the retrieval of nuclear hardware due to the thermal and radiation environment. A reactor located in shallow water may be found to be operating in a quasi-steady state critical condition. A means of safing the system (possibly remotely) must be devised. Candidate procedures include encapsulation or covering, drainage of water and destruction by explosive charges. Whatever mechanism is used, undue radiation exposure of the recovery team and additional dispersal of radioactive material should be prevented. A summary of the key considerations for implementation of radiological control during the Launch/Ascent Phase is presented in Table 5-13.

Table 5-13. Guidelines for Launch/Ascent Radiological Control Operations

1	Establish and control a 4 km exclusion radius around launch site
2	Provide rapid response impact recovery teams for KSC and down range safing and recovery of nuclear impacted material
3	Provide decontamination capability
4	Provide proper nuclear material handling tools
5	Provide means of safing a reactor in a quasi-steady state critical condition
6	Use experienced cross-trained personnel
7	Minimize exposure to recovery team
8	Prevent additional dispersal of radioactive material

5.3.4 MISSION CONTROL

The communications, tracking and command control network for nuclear missions originating from KSC includes the Launch Control Center, Mission Control Center, Data Relay Satellite System and the telemetry and tracking capability of the Manned Space Flight Network.

The nuclear safety responsibility rests with NASA-KSC and the USAF Eastern Test Range Safety Office until orbit is achieved. Included in this responsibility is the decision to terminate the launch and provide direction of the impact/recovery forces.

After orbit insertion, control and safety responsibility rests with the NASA Mission Control Center (MCC) and the Command and Control Room in a Space Base. Capability for telemetry/status monitoring and command control of a nuclear power module must be provided by both the Space Base and the MCC. The MCC will provide backup capability.

The present Manned Space Flight Network is not adequate at the 55° inclination orbit. The use of DOD facilities and additional relay satellites should be considered to provide rapid response capability as well as additional tracking data for orbit and impact determination.

A summary of the mission control considerations during launch and ascent is contained in Table 5.14.

Table 5-14. Guidelines for Mission Control During Launch/Ascent Operations

1	Establish nuclear safety responsibility with NASA-KSC and the ETR until orbit is achieved
2	Establish nuclear safety responsiblity with NASA-MSC during orbital operations
3	Control of nuclear power module must be provided by both a space base and the MCC
4	Consider additional tracking, command and telemetry network capability for missions in 55° inclination orbits

5.4 ORBITAL OPERATIONS SUPPORT

Support of manned nuclear missions in orbit will require essentially the same types of facilities and mission control capabilities as those presently in use for the Apollo and Sky Lab missions. The potential nuclear hazards and effects involved in orbital operations during a 10-year manned space mission are presented in Section 6.0. This sub-section will briefly address the ground support considerations characteristic of manned nuclear missions, as depicted in Figure 5-19 with emphasis on (1) Radiological Control and (2) Data Management.

The principle mission support interfaces with the nuclear hardware are identified in Table 5-15.

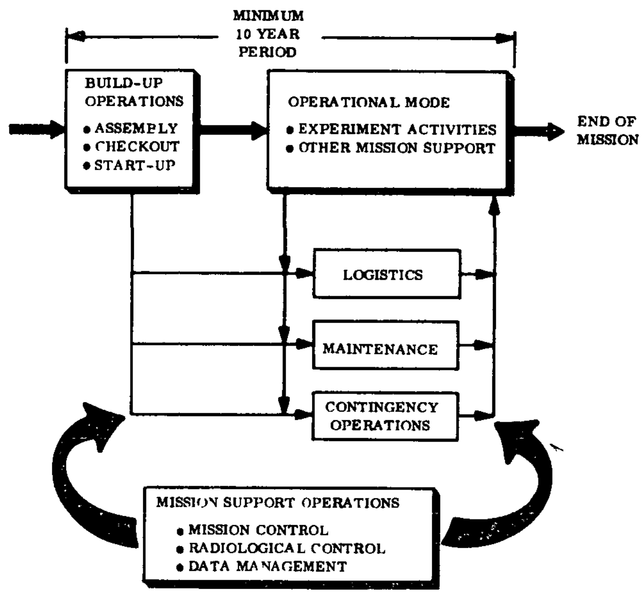


Figure 5-19. Mission Support for Orbital Operations

Table 5-15. Potential Nuclear Hardware Interfaces With Mission Support During Orbital Operations

NUCLEAR HARDWARE RELATED OPERATIONS / POTENTIAL MISSION SUPPORT INTERFACES	IN ORBIT: SPACE TUG	IN ORBIT: SPACE SHUTTLE	GROUND OPERATIONS: FLIGHT CREWS	MCC-COMMAND & CONTROL	MCC-TELEMETRY	MCC-DATA MANAGEMENT	MCC-BIOMEDICAL	DATA RELAY SATELLITES	RANGE TRACKING
BUILD-UP / POWER MODULE START-UP	⊗	⊗	⊗	×	×	×	⊗	×	×
OPERATIONAL MODE	×	×	⊗	⊗	⊗	⊗	⊗	⊗	×
LOGISTICS	⊗	⊗	⊗		×				⊗
MAINTENANCE	×	×	⊗		×	×	⊗	⊗	
CONTINGENCY OPERATIONS	×	×	⊗	⊗	⊗	⊗	⊗	⊗	⊗

POWER MODULES

ISOTOPES

5.4.1 RADIOLOGICAL CONTROL

Obtaining and recording the real-time integrated dose of each crew member is desirable, but probably not practical. Considerable radiological processing of dosimeters and urine specimens would be performed in orbit by the Base radiological control. However, selected integrated dose data (film emulsions, urine samples, etc.) can be processed on the ground to serve as a check and reduce the work load in the Base. Radiation control of samples and emulsions must be maintained during logistics operations to assure correct crew dose determination. In addition, tabulated crew radiation doses recorded by the base data management system can be transmitted to Mission Control for additional processing, analysis and mission planning. This sharing of the radiological data handling responsibility should be designed to prevent inadvertent overdoses to the crewmen and allow for effective scheduling of work and timely crew resupply. Figure 5-20 depicts the sharing of the radiological control load and other mission support functions by the base and mission control.

A more comprehensible discussion of radiological control in orbit is contained in Section 6.

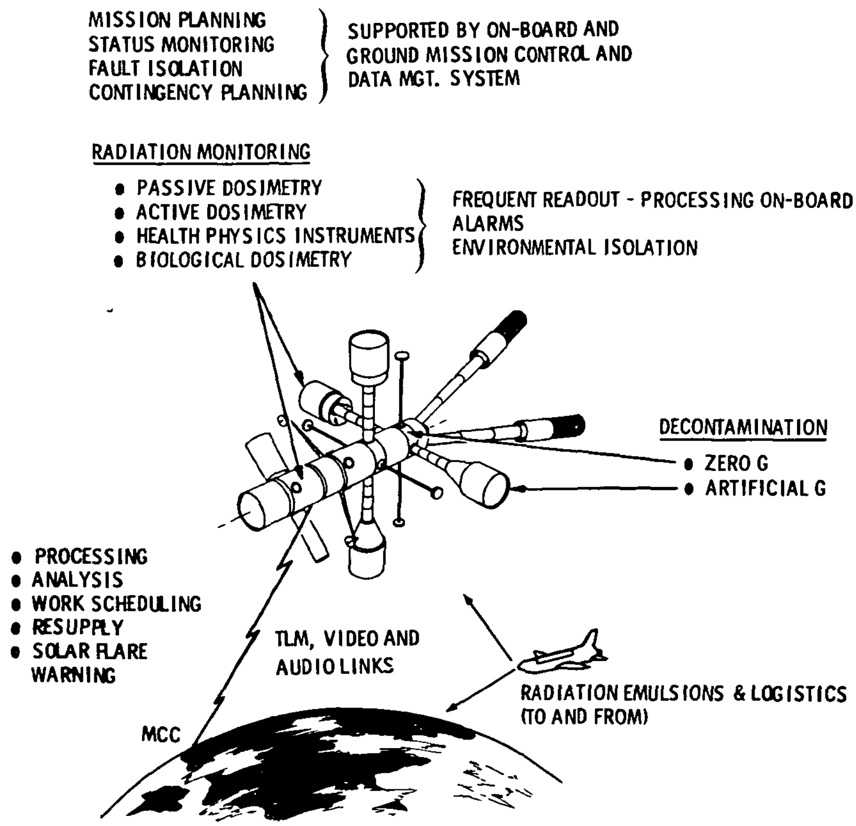


Figure 5-20. Mission Support During Orbital Operations

5.4.2 DATA MANAGEMENT

In addition to radiological data processing and analysis, ground systems will serve as a prime diagnostic and backup control center for the assessment of nuclear power module status. Shutdown and disposal functions must be capable of being directed and commanded from Mission Control.

Operating histories would be recorded and key data (temperature, power level, pressure) analyzed to detect abnormalities and provide advanced warnings so corrective actions can be taken in space and through logistic resupply.

5.4.3 MISSION SUPPORT GUIDELINES

Key mission support considerations during the orbital operations of a nuclear spacecraft are summarized in Table 5-16 below.

Table 5-16. Guidelines for Mission Support During Orbital Operations

1	Consider requirements for attended support of the MCC for the entire mission
2	Provide logistic resupply and processing of radiological dosimetry—emulsions and urine specimens
3	Provide adequate radiation control and shielding of logistic samples
4	Process integrated dose data on flight personnel and critical hardware and make necessary logistic/resupply plans
5	Provide nuclear system status and fault diagnostic support
6	Provide back-up evaluation and command and control capability
7	Provide and process complete power module and heat source operating histories as required
8	Provide advanced warnings of potential failures when possible
9	Provide advanced warning of solar flares

5.5 DISPOSAL/RECOVERY OPERATIONS SUPPORT

The principal functions involving the nuclear hardware during the Disposal/Recovery Phase are identified in Figure 5-21. The major mission support interfaces are listed in Table 5-17. The reactor power module is assumed to contain its own disposal system (Section 3). Prime tracking, telemetry and command control for reactor power module disposal into high earth orbit will be the responsibility of the Space Base and its crew. However, the MCC must provide back-up

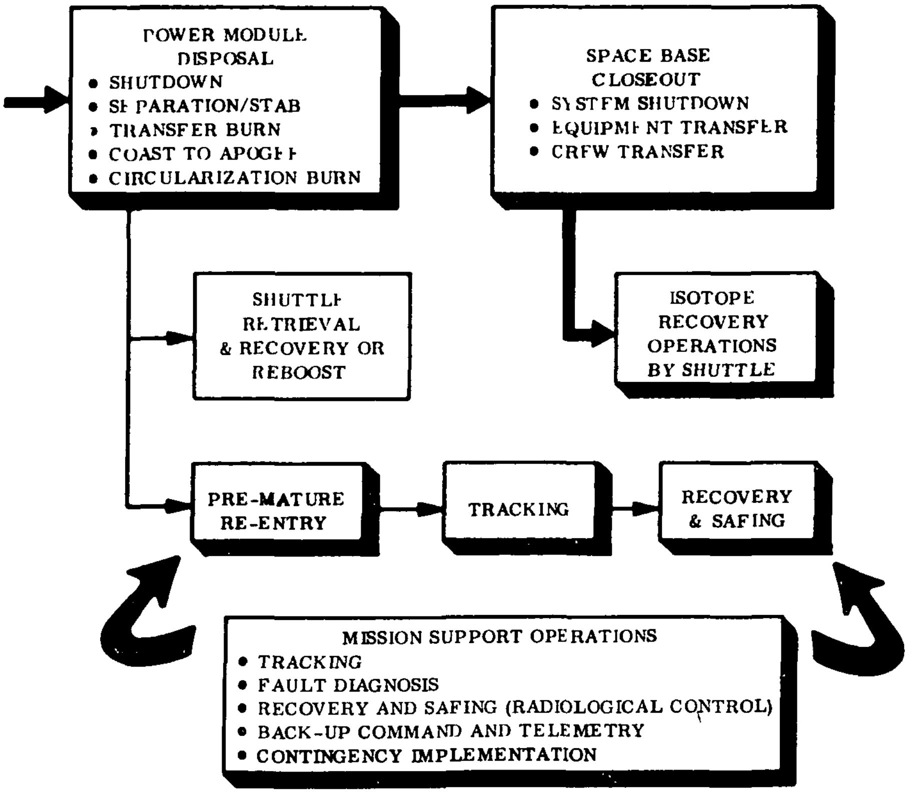


Figure 5-21. Disposal/Recovery Operations Support

capability. To provide this capability the power module must be equipped with its own on-board telemetry, tracking and command and control system capable of stimulation from either the Space Base or ground systems.

Prime command functions include control drum rotation, activation of shutdown systems, separation and stabilization, guidance alignment, thrust ignition and termination of the disposal system.

Tracking aid equipment and a transponder must be placed on the power module to assist long range tracking and computation of final orbit. Once final disposal orbit is achieved, all responsibility is with the MCC. As discussed in detail in Volume III, Part 2, there exist a number of unlikely but credible accident modes which may prevent a successful disposal to the desired high earth orbit and result in a reduced life orbit "premature reentry" of the power module. To minimize the hazards of this unlikely occurrence and of potential reentry it is important to

Table 5-17. Potential Nuclear Hardware Interfaces with Mission Support During Disposal and Recovery

Nuclear Hardware Related Operations		Space Shuttle	Base Crew & Systems	MCC Command & Control	MCC Telemetry	MCC Data Management	Data Relay Satellites	Range Tracking	Recovery Team	Shuttle Landing Site	Ocean	Continents & Islands	Tracking & Recovery Ships
POWER MODULE DISPOSAL	SHUTDOWN		x	x	x		x						
	SEPARATION & STABILIZATION		x	x	x	x	x	x					
	TRANSFER BURN		x	x	x	x	x	x					
	COAST TO APOGEE			x	x	x	x	x					
	CIRCULARIZATION BURN			x	x	x	x	x					
POTENTIAL RE-ENTRY	TRACKING				x	x		x					x
	RECOVERY & SAFING	A				x		x	x	A	x	x	x
SPACE BASE CLOSEOUT	SYSTEM SHUTDOWN		o	o	o		o						
	EQUIPMENT TRANSFER	o	o										
	CREW TRANSFER	o	o										
	ISOTOPE RECOVERY	o	o				o	o	o	o		o	o
ALTERNATE - SHUTTLE RECOVERY OF REACTOR		A	A	A				A	A	A			

LEGEND
x REACTOR POWER MODULE
o ISOTOPE SYSTEMS
A ALTERNATE

track and determine the potential impact area, such that when impact occurs, the power module can be readily located so controlled access and decontamination can be initiated.

Key to the effective implementation of this effort is (1) the incorporation of tracking and location aids on the reactor shield such as beacons, dye markers and underwater pingers and (2) the availability of a trained quick reaction impact recovery team which can be flown to the land or shallow water impact area. No attempt at recovery is necessary in deep ocean areas.

The NASA Space Shuttle provides an alternate and versatile means of achieving power module or other nuclear hardware disposal. The Shuttle could well serve as the prime mode of recovery for isotope systems and as prime or back-up for reactor power module disposal or recovery. In either case, the inherent reliability of the Shuttle in reentry and return to the

designated landing site makes a reentry and recovery accident very unlikely. The use and safety aspects of the Shuttle as a means of transporting nuclear hardware has been evaluated and is discussed in some detail in Volume IV of this report.

5.5.1 DISPOSAL/RECOVERY OPERATIONS GUIDELINES

Key considerations during disposal and recovery operations are summarized in Table 5-18.

Table 5-18. Guidelines for Mission Support During Disposal & Recovery Operations

1	Provide prime control for reaction power module disposal to high earth orbit from Space Base
2	Provide back-up tracking, control, telemetry capability for reactor power module disposal operations from the MCC
3	Provide supporting diagnostic data for power module and disposal system status and fault isolation
4	Provide tracking and location devices on nuclear hardware
5	Provide determination of interim and final orbits from (MCC)
6	Provide determination of potential impact areas of a reactor power module or an aborted isotope recovery mission
7	Provide technical and hazard data for advanced warnings of impact to proper authorities
8	Consider use of floatation gear on isotope systems
9	Provide rapid response recovery teams to locate control, safe and decontaminate impact areas
10	Provide recovery capability in shallow water areas
11	Provide recovery of all isotope devices
12	Consider use of Space Shuttle as a mode of disposal recovery of reactor power modules and prime mode of recovery for isotope systems
13	Provide recovery and radiological control teams at shuttle landing site

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SECTION 6
SPACE BASE OPERATIONS - RADIOLOGICAL HAZARD ANALYSIS

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SECTION 6
SPACE BASE OPERATIONS - RADIOLOGICAL HAZARD ANALYSIS

6.1 GENERAL

The purpose of this section is to identify the effects of potential radiological hazards on a Space Base and to provide an assessment of their influence on design and operations. Primary emphasis is on nuclear safety of the crew, subsystems and experiments in Space Base operations as opposed to Section 5 which deals with mission support operations and also Volume III of this study which deals with terrestrial safety associated with the reactor power module. The radiological hazards considered are those which are directly associated with nuclear radiation and also those non-nuclear hazards which may be associated with the presence of nuclear materials, e.g., heat, chemical reactions, etc.

6.2 POTENTIAL HAZARD IDENTIFICATION

Potential hazards have been grouped into two categories: 1) hazards associated with the normal operation of a Space Base and 2) hazards arising from accidental (unplanned) events. Associated with each of these categories are a hazard source, the condition of the source and the resulting potential hazard. The hazard source, its condition, and the effects on a Space Base varies according to the mission phase. Therefore, it is necessary to identify the existence of the potential hazard and its resulting impact on a Space Base crew, subsystems and experiments according to mission phase. Sections 6.2.1 and 6.2.2 delineate the rationale used in screening the potential hazards, and identify in accordance with the baseline mission and design features, those potential hazards which require further evaluation.

Tables 6-1 and 6-2 in the following sections show the potential hazards identified as a function of hazard source and mission phase. These tables represent a preliminary evaluation of the existence of a hazard. The designation "N. A." (not applicable) indicates that the particular source condition cannot occur during the respective mission phase. The designation "NO" indicates that the source condition does not pose a hazard or poses a negligible hazard due to baseline design or operational features. In the following discussions, these features are noted, where applicable, and underlined for emphasis. The designation "YES" implies that

a hazard may exist and requires further investigation to determine the hazard category. Evaluations as to the effects of these potential hazards and associated preventive and remedial measures are discussed in Section 6. 3.

6. 2. 1 NORMAL OPERATIONS

Hazards associated with the normal operations are those which are inherent to the operations or configurations of the Space Base program. Consistent with the baseline mission and configuration, four categories of hazard sources have been identified. These are: 1) the natural radiation environment, 2) the Space Base reactor power modules, 3) the interfacing vehicles associated with the Space Base and 4) equipment associated with the Space Base Experiment Laboratory facilities.

The following discussions identify the rationale used to generate the preliminary hazard identifications shown in Table 6-1 under normal operations for each hazard source.

6. 2. 1. 1 Natural Radiation Environment

For the orbit altitude and inclination of interest (500 km, 55^{o} inclination) the natural radiation environment consists primarily of geomagnetically trapped electrons and protons, galactic cosmic radiation, and radiation associated with solar flares. As can be seen from Section 3. 8. 1, the natural radiation environment presents a significant source of radiation for all portions of the mission, except prelaunch. The extent of the effect of the natural radiation environment on a Space Base design and operations is evaluated in Section 6. 3. 1.

6. 2. 1. 2 Reactor Power Modules

Four potential hazard source conditions have been identified for the Reactor Power Modules under normal conditions. These are: 1) shutdown without prior operation at design thermal power level (but after low level criticality checks), 2) operation at normal thermal power level (330 kWt), 3) shutdown after normal operation, and 4) operation at emergency thermal power level (600 kWt). The preliminary assessment of the impact of these conditions as pertains to the various mission phases is discussed below.

Table 6-1. Potential Space Base Hazard Identification Normal Operations

Hazard Source	Source Condition	Potential Hazard	Mission Phase			
			Prelaunch	Launch/Ascent	Orbital	End-of-Mission
<u>Natural Radiation Environment</u>						
Geomagnetically Trapped Protons and Electrons and Galactic Cosmic		Excessive Radiation	N. A.	Yes	Yes	Yes
Solar Radiation	Solar Flare	Excessive Radiation	N. A.	Yes	Yes	Yes
<u>Reactor Power Modules</u>	Shutdown (No Operating History)	Excessive Radiation	No	No	No	N. A.
	Normal Operating Power	Excessive Radiation	N. A.	N. A.	Yes	N A.
		Thermal Interference	N. A.	N. A.	Yes	N. A.
	Shutdown (Post Operation)	Excessive Radiation	N. A.	N. A.	Yes	Yes
	Emergency Operating Power	Excessive Radiation	N A.	N. A.	Yes	N. A.
		Thermal Interference	N. A.	N. A.	Yes	N. A.
<u>Interfacing Vehicles</u>						
Reusable Nuclear Shuttle	Shutdown (Post Operation	Excessive Radiation	N. A	N. A.	Yes	N. A.
	Normal Power (Thrusting)	Excessive Radiation	N. A	N. A.	Yes	N. A.
(Reactor Power System)	Shutdown (Post Operation)	Excessive Radiation	N A	N. A	Yes	N A.
	Normal Operating Power	Excessive Radiation	N. A	N A	Yes	N A.
<u>Experiment Laboratories</u>						
X-Ray Equipment (Dynamic Generators)	As Installed	Excessive Radiation	Yes	N A	Yes	N. A.
Open Radioisotope Sources/Tracers	Stored	Excessive Radiation	No	No	No	No
	In Use	Radioactive Contamination	N. A	N A	Yes	N A.
Closed Isotope Sources/Capsules	As Installed	Excessive Radiation	Yes	Yes	Yes	Yes

Prelaunch. Of the reactor power module conditions identified above, only the first is applicable to the prelaunch phase. This is true if testing prior to reactor full power operation in orbit is restricted to low power level criticality checks. For example, restricting criticality testing to a total of 30 kW-hr at power levels of a few hundred watts (thermal), results in a maximum dose rate (immediately after testing) of 1.3 mrem/hr at a position 3 meters from the shielded reactor. Within two weeks after testing, this dose rate would decay to 0.6 mrem/hr, a value which is within the National Committee for Radiation Protection (NCRP) recommendations for maximum exposure of radiation workers (Reference 6-11) and which is sufficiently low as not to present a threat to the Space Base crew, experiments, and subsystems which could be nearby during prelaunch activities.

Launch/Ascent. Limiting operation of the reactor, as discussed in the prelaunch phase, also results in no hazard to the Space Base program elements during launch/ ascent and precludes the existence of the other reactor hazard source conditions during this phase.

Orbital. During this phase the conditions associated with the reactor power module during operation and shutdown after full power operation must be evaluated in conjunction with the natural environment to assess the impact of the resulting radiation environment on a Space Base and those vehicles which interface with the Space Base. In addition to the radiation environment, the reactor power module radiators may present a source of infrared radiation which could interfere with logistic and experiment vehicle attitude control system scanners during final rendezvous maneuvers. (See Section 6.3.1.)

End-of-Mission. Since the End-of-Mission (EOM) phase of the mission is primarily concerned with closeout of a Space Base facility, the only reactor power module source condition which applies under normal operations is a shutdown reactor after normal operation. Reactor Power Module EOM is discussed separately in Section 7.3.4, Reactor Disposal Techniques.

6.2.1.3 Interfacing Vehicles

As discussed in Section 3.8.3, three types of vehicles which interface with the Space Base are potential sources of radiological hazards. These are: 1) the Reusable Nuclear Shuttle (RNS), 2) the Orbital Propellant Storage Depot (OPSD), and 3) free-flying (detached) experiment modules. Of the three, the RNS (Reference 6-2) represents the most significant source of direct radiation because of its nuclear engine propulsion system. Although the OPSD and experiment modules are only sketchily defined at present, they are being considered here because of the possibility of nuclear electrical power systems being incorporated into the designs.

Prelaunch and Launch/Ascent. No hazards from the RNS and OPSD are experienced during these phases since no operational interface exists. Experiment modules which may contain isotope power sources must be considered. (See Section 6.3.1, 6.3.)

Orbital. During the orbital phase, a Space Base may interface with these vehicles as described in Section 3.5. Therefore, all hazard source conditions must be evaluated as to their potential effect on the Space Base during orbital operations. (See Section 6.3.1.6.)

End-of-Mission. Closeout of a Space Base does not require interfaces with these vehicles. (See Section 7.3.4 for a discussion of reactor disposal and Section 7.3.2 for isotope handling procedures.)

6.2.1.4 Experiment Laboratories

As discussed in Section 3.8.4, there are three categories of hazard sources associated with the Space Base experiment laboratories: 1) dynamic sources, 2) open isotope sources, and 3) closed isotope sources. Since definition of the characteristics and location of these sources is insufficient to allow evaluation of specific concepts, several assumptions have been made to allow preliminary identification of safety considerations. In addition, Sections 7.3.1 and 7.3.2 discuss precautions and considerations in the handling of isotope systems.

Prelaunch. It is assumed that dynamic equipment may be exercised during prelaunch operations in order to verify satisfactory operation and installation. However, passive equipments such as isotope sources would be stored with appropriate containment. (See Section 7.3.2.) Therefore, during normal operations, the use of isotope tracers would not be applicable to the prelaunch phase, whereas unrestricted checkout of x-ray equipment could affect equipments and personnel. Similarly the interactions with isotope capsules (which may, for example, contain several hundred thermal watts in heater forms) must be evaluated. Preliminary analysis of the quantity of tracers likely to be required to support experiment laboratories, indicates microcurie inventories which would pose a negligible hazard from direct radiation.

Launch/Ascent. It is assumed that dynamic generators are not powered during this phase. The prelaunch comments otherwise apply.

Orbital. Considerations associated with operation of the x-ray equipment, storage of tracers and installed isotope capsules are the same as in the prelaunch phase. However, isotope tracers must be considered from the standpoint of quantities involved and potential by-products of usage, e.g., gaseous by-products which could be dispersed, and waste containing trace quantities of isotopes.

End-of-Mission. It is assumed that dynamic generators will be secured after their useful life, in such a manner as to preclude their operation during the close-out of a Space Base. Interactions with the closed and open isotope sources would be the same as during the orbital phase. As a matter of policy, these isotopes should be recovered and returned to earth to preclude dispersion in the atmosphere if a Space Base were to be allowed to reenter and burn up. (See Section 7.3.2.1 for guides to isotope capsule design requirements.)

6.2.2 ACCIDENT CONDITIONS

Table 6-2 correlates the potential radiological hazard sources associated with a Space Base Program to the accidental source conditions and the resulting hazards as a function of mission phase. The following discussion identifies the rationale for the preliminary hazard identification.

6.2.2.1 Reactor Power Modules

Five accidental source conditions have been identified with the reactor power modules. As can be seen from Table 6-2, these conditions may result in a hazard during each of the mission phases with the exception of the damaged reactor shield. In this case, the limitation on prelaunch reactor operation (only low power level criticality checks - see Section 6.2.1.2) minimizes the fission product inventory and therefore the source strength of the reactor. Maximum damage, i.e., total removal of the shielding would result in a dose rate of about 30 mrem/hr at a distance of 10m (33 ft) from the bare core. The low power level operating history would also result in a negligible quantity of tritium produced in the shield (Reference 6-3). Whereas, these conditions may be of concern to launch pad support personnel (see Section 5.1) the effect on the Space Base components and crew would be negligible during the prelaunch and launch/ascent phases and indeed prior to initial operational startup of the reactor.

6.2.2.2 Interfacing Vehicles

These vehicles are encountered by the Space Base only during operations in orbit; therefore, consideration is restricted to the orbital phase. As discussed in Section 3.8.3, the OPSD has been assumed to employ a reactor(s) similar to the Space Base power system, and therefore, similar source conditions and hazards would apply.

6.2.2.3 Experiment Laboratories

The accidental source conditions identified for the experiment laboratory sources are of a generic nature reflecting the lack of specific design data. In general, these conditions must be considered for all operational phases with the exception of the following situations. It is assumed that dynamic generators are not powered during launch/ascent and therefore cannot be turned on. In the case of the isotope sources, it is assumed that should these devices be launched with Space Base modules, the modules would not be manned, and, therefore, internal exposure of the crew would be precluded. The same reasoning applies to the prelaunch phase where pad personnel could be exposed (see Section 5.1) but Space Base crew would not be exposed.

6.3 HAZARD EVALUATION

This section considers the potential hazards identified in Tables 6-1 and 6-2 of Section 6.2 and evaluates the effect of these hazards on a Space Base Program. The evaluation follows the format used in the previous section, initially considering hazards associated with normal operating conditions and subsequently those associated with accidental conditions. Fault trees developed to identify the potential causes of these hazards are contained in Appendix B.

6.3.1 NORMAL OPERATIONS EVALUATION

Considering the hazard identification of Table 6-1, the majority of the potential hazards to a Space Base identified under normal operating conditions, are associated with the orbital portion of the mission - Launch/Ascent (Rendezvous and Docking), Orbital, and End-of-Mission. Therefore, major emphasis has been placed on the operations of the Space Base in orbit. Those considerations dealing primarily with the Experiment Laboratory hazard sources are treated specifically in Section 6.3.1.7, and cover the sole topics associated with Prelaunch.

6.3.1.1 Environment Components

Under normal operating conditions, the radiation environment in and around the Space Base

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is due to four sources, 1) Geomagnetically trapped and galactic cosmic radiation, 2) Reactor power module radiation environment, 3) Radiation sources distributed about the Space Base, and 4) Solar radiation (principally solar flares).

Figure 6-1 shows the dose rate from the geomagnetically trapped protons and electrons as a function of Space Base module cylindrical wall thickness for skin and depth dose. Based on Space Base studies (Reference 6-4), 1.6 g/cm^2 is a representative value for cylindrical wall effective shielding, including the effects of internal equipment location.

Similarly, Figure 6-2 shows the isodose contours induced by the two reactors, each operating at its normal power level of 330 kWt. As can be seen from this figure, the dose rate from the reactors, over the habitable area of the Space Base varies from 1.0 to 0.35 mrem/hr. Since the vehicle structure and equipments provide essentially no attenuation of the gamma and neutron radiations from the reactor, this is the range of dose rates experienced inside the Space Base due to the operating reactors. Comparing these rates with the dose rates from the natural environment (exclusive of solar flares) shown in Figure 6-1, the depth dose due to the natural environment is 2.8 to 8 times the dose due to the reactor environment. The comparatively low dose rate from the reactors is due primarily to the extensive, shaped 4π reactor shield employed.

The remaining significant localized source of radiation on the Base Space comes from isotope capsules which may be associated with experiment laboratories. Although the location and size of these capsules is as yet undefined, an estimate of the effect of distributed capsules may be evaluated by considering the use of an isotope powered waste management system. This system is a candidate experiment for Advanced Technologies and may be used throughout future manned space vehicles. One unit presently under development employs a capsule containing 400 watts of Plutonia ($^{238}PuO_2$) fuel in a shielded configuration (Reference 6-5).

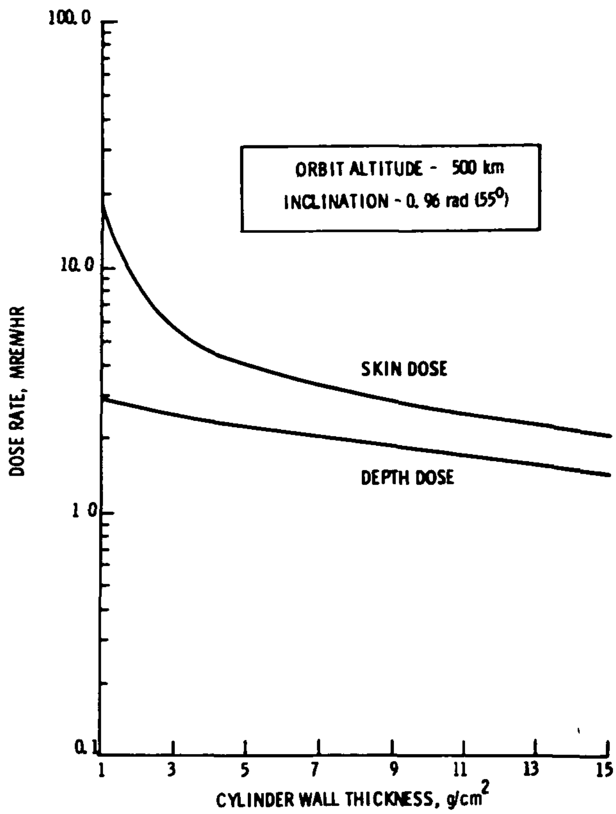


Figure 6-1. Radiation Dose Rate On-Board the Space Base as a Function of Cylindrical Wall Thickness for Geomagnetically Trapped Protons and Electrons, Including Galactic Cosmic Radiation Rate of 0.033 mrem/hr

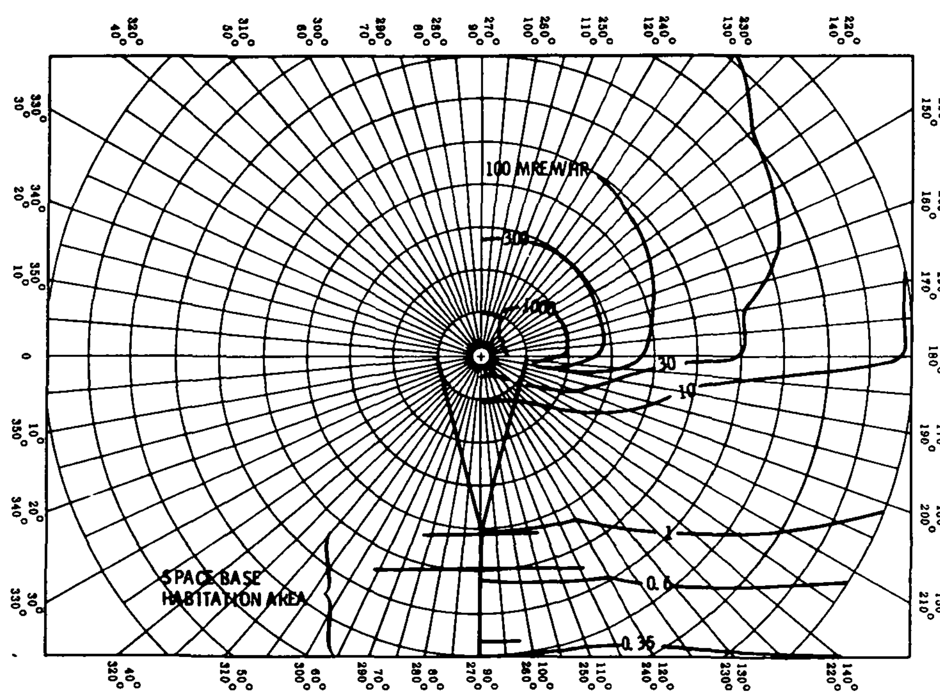


Figure 6-2. Reactor Power Module Isodose Contours

The combined neutron and gamma dose rates from this radioisotope source result in a dose rate of 0.6 mrem/hr at 1 meter from the capsule. In order to evaluate the effect of distributed sources about a Space Base, the contribution of these radioisotope sources to the composite radiation dose rate was evaluated using the previously discussed capsule as a baseline. Figure 6-3 shows the localized effect of radioisotope capsules of this type distributed about the vehicle. The inset shows the dose rate as a function of distance from the capsule source, where the closest approach is limited to 1 meter by the geometry of the system. A review of the Space Base concepts indicated that the location closest to the reactors, where waste management facilities are planned to be located is on the artificial "g" module habitation decks. Combining the Waste Management System, radioisotope sources, reactors and continuous natural environment dose rates at this location would give the highest localized dose rate in the vicinity of a distributed radioisotope source of this type. The localized effect is shown by superimposing the radioisotope source dose vs. distance on the composite curve. The maximum dose rate curve would be the dose rate based on 100 percent occupancy of the area adjacent to the Waste Management System. Review of the projected crew traffic indicated that maximum occupancy of the artificial "g" habitation areas would be more nearly 50 percent. Therefore, the curve based on the average 50 percent occupancy is more realistic. As can be seen from Figure 6-3, this combined dose rate is nearly equal to the maximum dose rate from the reactors and natural environment at the reactor boom/zero "g" interface. Therefore, for analyses purposes, the dose rate at this point was assumed uniform throughout the Base as representative of deployment of radioisotope capsules throughout a Space Base vehicle.

Figure 6-4 shows the solar flare event dose from a single event, considering the effective cylindrical wall thickness. For the range of flight times considered, up to 1 year, the solar flare model predicts a 95 percent confidence level of one flare occurring during the first 5 weeks, with a second event possible thereafter.

6.3.1.2 Crew Effects - Normal Radiation Environment

The crew of a Space Base will be exposed to the environment described in the preceding section during their tour of duty on board the Base. For this preliminary evaluation the

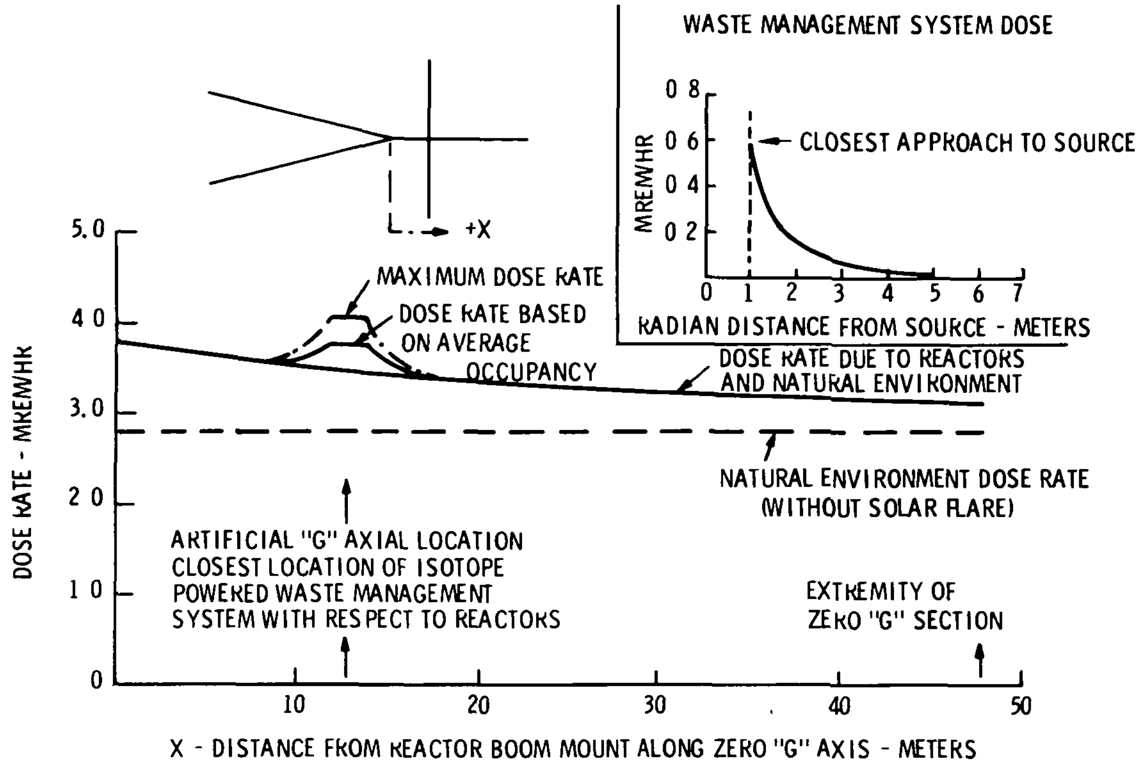


Figure 6-3. Localized Effect of Isotope Powered Waste Management Systems

specific location of individual crew men in the Base is not important since the dose rate in different portions of the Base may easily be perturbed up to the maximum (habitable location closest to the reactor) by localized sources (see Figure 6-3). Therefore, in evaluating overall crew exposure, a uniform environment may be established on the Space Base while the variations in the environment as a function of position must be considered for evaluation of other periods of exposure such as rendezvous and docking and EVA operations. The crew radiation limit guidelines employed are those previously discussed in Section 4.2.1.

6.3.1.2.1 Rendezvous and Docking Operations

In addition to the time spent on the Base, the crew will be exposed to the natural radiation environment and the reactor environment during transfer to and from the Base. Depending on the selected approach path to the final docking point, a more severe reactor radiation environment may be encountered than would be experienced during normal activities on the Space Base. Since it is assumed that the Space Base may take any orientation with respect

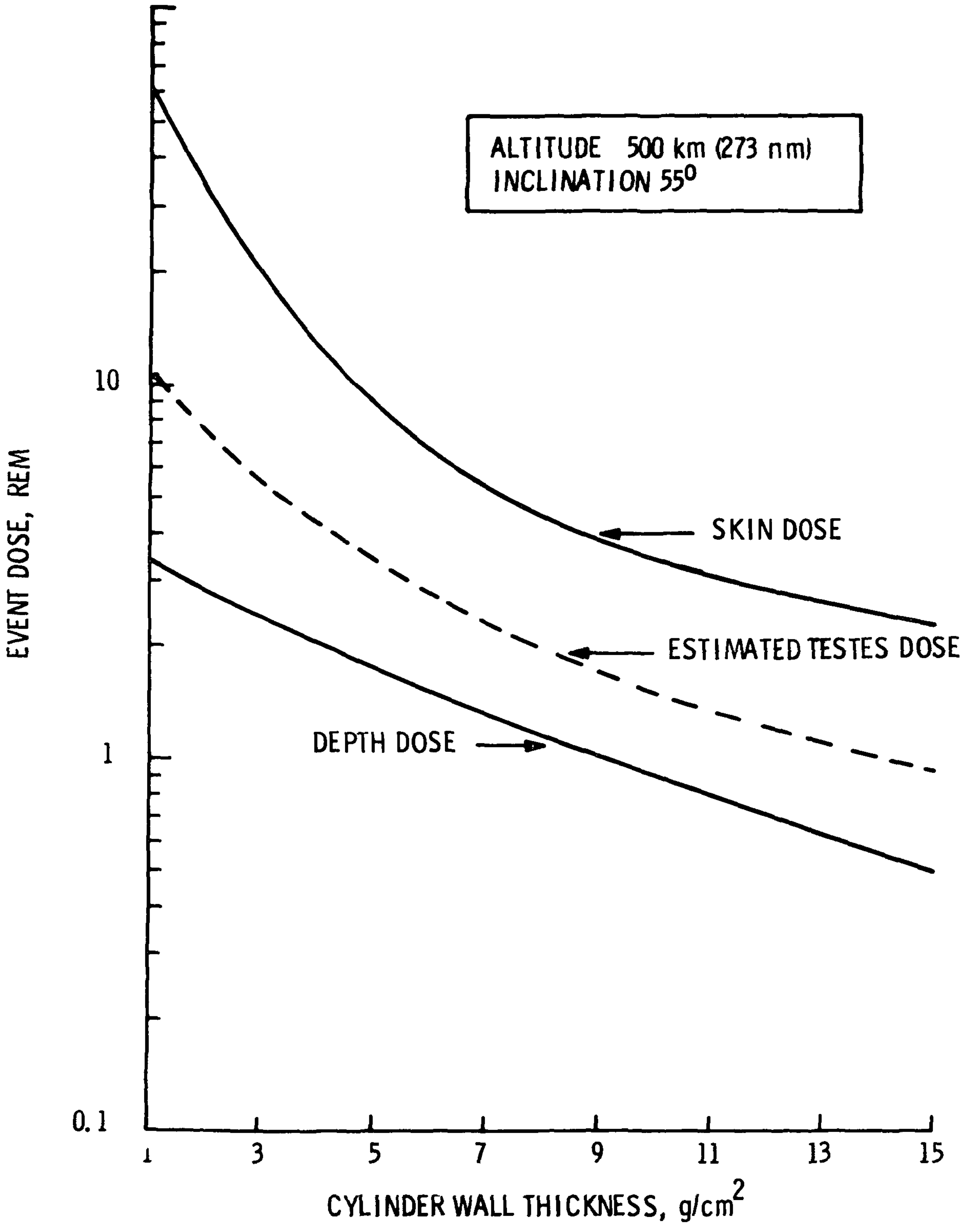
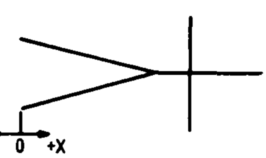


Figure 6-4. Solar Particle Event Radiation Dose

to the orbit plane, there exists the possibility that the approaching vehicle could encounter the more lightly shielded reactor environment. This would occur, for example, should rendezvous be attempted from the -x direction (see Figure 6-2). In order to determine the severity of this condition, and to evaluate the requirement for rendezvous restrictions, a terminal rendezvous approach was postulated, where the approach is along the -x axis of the Space Base (proceeding from -x to +x) with docking at the extreme end of the zero "g" section of the Base. This approach would expose the crew to the highest reactor radiation environment.

Figure 6-5 shows the reactor induced dose rate profile along the -x to +x axis of the Space Base, where the origin of the abscissa is at the reactor mount. The same figure shows the velocity/distance braking gates that a shuttle would use in final rendezvous maneuvers. Based on these data, a total integrated dose due to the reactor environment is approximately 5 mrem. In addition, the crew would be exposed to the natural radiation environment. Since resupply missions could require 3 to 17 orbits until docking (Reference 6-6), the accumulated dose due to the natural environment during this time period would range from 13 to 19 mrem. (Note: a portion of the 17 orbit profile is spent at low altitude where a lower natural environment dose rate prevails.) Therefore, the maximum dose for a nor-

SHUTTLE RENDEZVOUS GATES	
VELOCITY	DISTANCE FROM DOCK
<9.15 m/sec (<30 ft/sec)	1830-915 m (6000-3000 ft)
<6.1 m/sec (<20 ft/sec)	915-460 m (3000-1500 ft)
<3.0 m/sec (<10 ft/sec)	460-150 m (1500-500 ft)
<1.5 m/sec (<5 ft/sec)	150-15 m (500-50 ft)
<0.15 m/sec (<0.5 ft/sec)	15-0 m (50-0 ft)



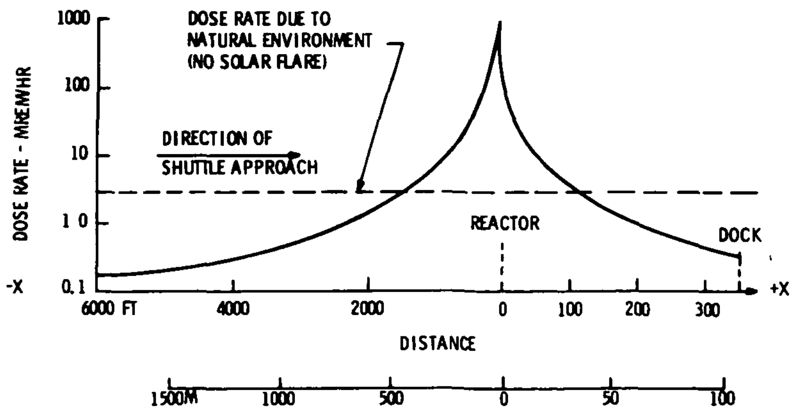


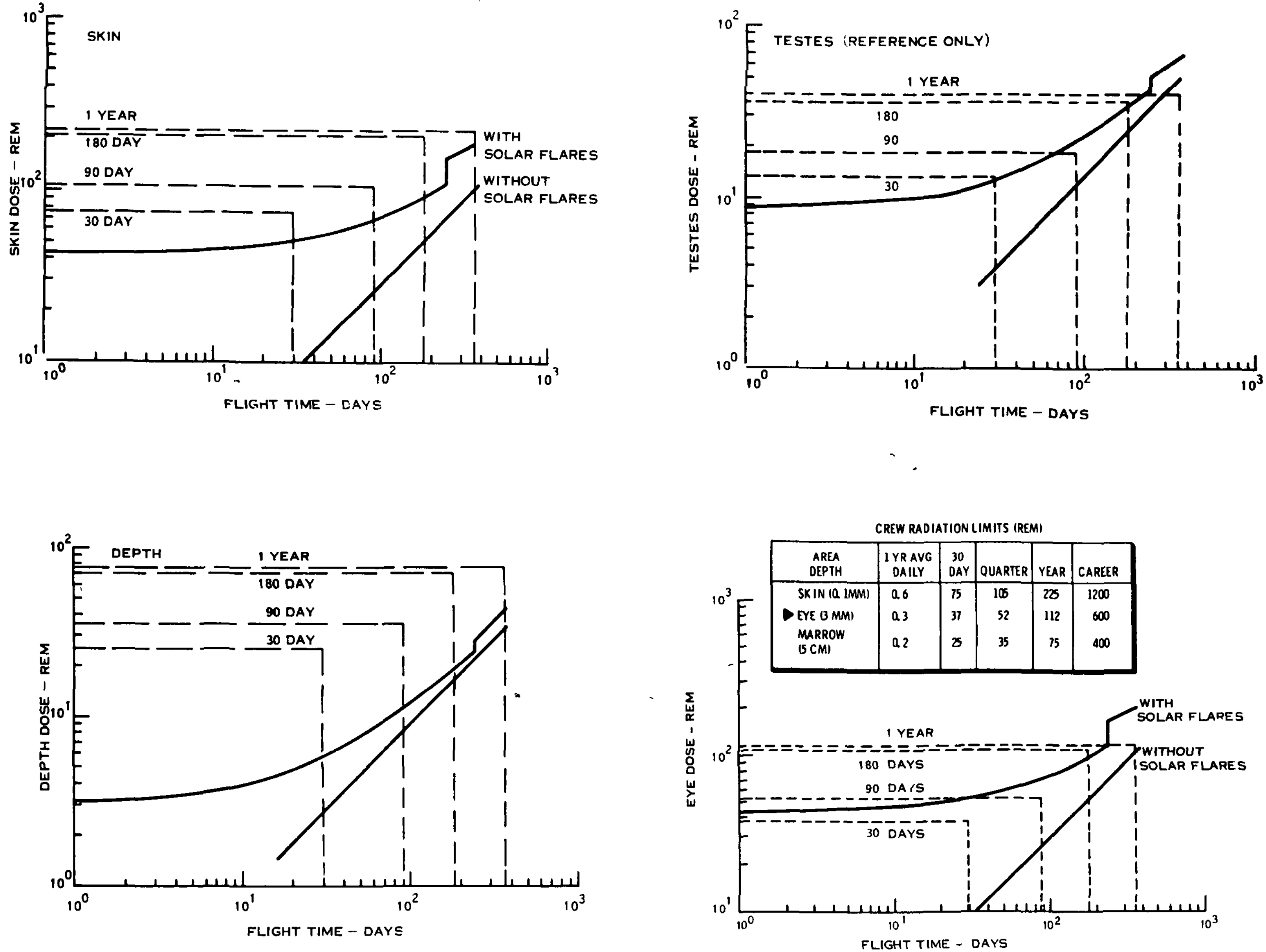
Figure 6-5. Reactor Radiation Dose Profile and Shuttle Rendezvous Gates

mal docking maneuver would expose the crew to a total of 18 to 24 mrem. Selection of an approach direction with a less severe reactor environment, e.g. from the +x direction, could reduce the reactor contribution to the dose to an essentially negligible quantity. It can be seen that reactor systems pose a negligible hazard to the crew during rendezvous and docking, providing that nominal braking gates are adhered to. Shuttle loiter, if allowed in the lightly shielded area of the reactor, could expose the transfer crew to the allowable average daily depth dose of 0.2 rem within a time period of as little as 12 minutes. Whereas, approaches from any direction other than from the lightly shielded area of the reactor would provide essentially unlimited loiter time. It is therefore concluded that maximum advantage be taken of the reactor shielding characteristics in specifying normal shuttle approaches in order to minimize crew exposure during transfer to and from the Space Base. However, contingency operations would allow a nominal approach from any direction without exposing the crew to a hazard which could be categorized as greater than Safety Negligible.

6.3.1.2.2 On-Board Exposure

During the entire duration of his mission, a crew member will be exposed to the combination of environments discussed in Section 6.3.1.1. A major uncertainty in the total dose received, is the number and intensity of Solar Flares. Considering the radiation exposure limits shown in Section 4 and using the solar flare event model shown in Section 3.8, an estimate can be made of the degree of crew exposure as a function of mission time. The requirement for additional shielding or for storm shelters can also be estimated.

Figure 6-6 shows the integrated dose to various parts of the body as a function of mission duration. The solid lines represent the accumulated dose both with and without flare events. The "step" in the plots, which include solar flare dose, reflects the event model which predicts a 95 percent confidence of one flare in the first 35 weeks and a second flare with 95 percent confidence after 35 weeks. The dashed lines indicate the suggested exposure limits for various time periods. The testes dose is shown for reference only, since the testicular dose limits are considered as risk versus gain considerations rather than a design criteria (see Section 4.2.1).



CREW RADIATION LIMITS (REM)

AREA DEPTH	1 YR AVG DAILY	30 DAY	QUARTER	YEAR	CAREER
SKIN (0.1MM)	0.6	75	105	225	1200
▶ EYE (3 MM)	0.3	37	52	112	600
MARROW (5 CM)	0.2	25	35	75	400

Figure 6-6. Crew Dose as a Function of Mission Duration @ 500 km (270 nm, 55° Inclination

As can be seen from Figure 6-6, the accumulated dose from all sources, except solar flares, is always well within the recommended limitations for the skin, depth and eye dose locations. When the dose due to solar flares is included,the depth and skin dose are still within limitations, however, the dose to the eye is exceeded significantly when mission durations of one year and greater are considered. The fact that solar flares cause the eye dose limitations to be exceeded indicates that additional protection against the flare environment may be required, e.g., storm shelters, in the case of longer missions (one year and longer).

Figure 6-7 shows typical storm shelter characteristics required to bring the accumulated yearly dose to within guideline limitations. Characteristics are given for both the eye and testicular doses. Three types of shelters are considered: 1) Spot shielding where selected areas of the base would be provided with shielding in addition to the nominal 1.6 g/cm^2; 2) Uniformly increasing the effective outer shell shielding and 3) Treating a central tunnel configuration (Reference 6-7) as a storm shelter. The third case allows optimization on a shield weight basis between shielding provided solely for solar flare protection and the protection afforded from the remaining radiation environment (see insert in Figure 6-7).

CONFIGURATION	EYE		TESTES	
	OUTER SHELL G/CM^2	STORM SHELTER G/CM^2	OUTER SHELL G/CM^2	STORM SHELTER G/CM^2
BASELINE (SPOT SHIELD SHELTER)	1.6	3.4	1.6	N/A
UNIFORM SHIELDING	2.5	0	6.5	0
CENTRAL TUNNEL SHELTER	2.0	1.2	6.0	3.6

TUNNEL SHELTER WEIGHT TRADE-OFF

- MODULE DIAMETER - 33 FT
- TUNNEL DIAMETER - 10 FT

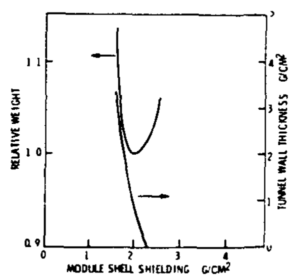


Figure 6-7. Storm Shelter Parameters

The concepts described in Figure 6-7 assume the addition of shielding to the main spacecraft structure. In providing protection for the eye (which appears to be the limiting dose area) consideration can be given to providing localized protection, e.g., helmets. The approach might allow additional operational flexibility but would have to be evaluated on the basis of overall mission risk/value considerations. Since geomagnetic shielding essentially eliminates the solar flare environment at 30^{o} orbit inclinations the solar storm shelter conclusions apply only to orbits above 40^{o}, in particular the 55^{o} inclination orbit.

6.3.1.2.3 EVA Exposure

During EVA activities the astronaut will not be afforded the protection of the Space Base structure and therefore, will encounter somewhat higher dose levels than during on-board exposure. In addition, his location with respect to the Space Base is important due to the variation of the reactor induced radiation field. Figure 6-8 and its accompanying table indicate the periods of time required to accumulate various dose levels during EVA, in different regions around the Space Base. The data is presented for the two reference orbit inclinations. The region shown in the figure corresponds to the isodose regions shown in Figure 6-2. The accumulated doses also include passage through the South Atlantic anomaly. Figure 6-8 illustrates the importance of astronaut location during EVA. In particular, if work is required in the vicinity of the reactors, the allowable EVA time may be less than one hour. In order to maximize EVA times and minimize dose, EVA should be planned for orbits that do not intercept the South Atlantic anomaly.

6.3.1.2.4 Crew Protection Design and Operational Considerations

Those aspects of crew protection addressed in this section, deal with the broad design and operations considerations which can significantly impact the nuclear safety of a Space Base mission. The crew protection design and operations guidelines are summarized in Table 6-3.

Principal consideration should be given to provision of (1) radiation shield e.g., solar flare shelters, (2) on-board radiation monitoring and warnings, and (3) regulation of crew operations, e.g., adherence to EVA, loiter, rendezvous and crew dose guideline operational restrictions.

At present, the only practical concept for providing shielding against the radiation environment to be encountered by the Space Base is massive, passive shielding. Active shield concepts such as plasmas and magnetic shields have been studied but currently lack development and may have considerable impact on the vehicle configuration (Reference 6-8).

Table 6-3. Crew Protection Guidelines

DESIGN

- Provide Storm Shelter facilities for refuge from solar flare events (high inclination orbits such as 55°)
- Consider localized protection for the eyes in relatively high radiation areas (e g , use of helmets)
- Provide on-board radiological monitoring of radiation dose accumulated by the crew
- Provide a central on-board warning system for monitoring and alerting against radiological hazards

OPERATIONS

- *Maintain nominal braking gate velocities*
- Minimize loiter time in the vicinity of the reactors
- Establish crew rotation procedures in conformance with career and periodic dose guidelines
- *Restrict EVA during orbits intercepting the South Atlantic anomaly*
- Limit EVA duration as a function of the variation with position in radiation levels due to the reactor(s)
- Take advantage of reactor shielding characteristics in implementing approach and loiter operations
- Coordinate EVA with the Radiological Safety Office to ensure safe EVA environment at the time of implementation

The natural radiation environment is the major radiation component encountered by the Space Base since the reactor dose is greatly attenuated due to the degree of shielding provided by the reactor shield (see Section 3.8.2.1). Of the natural environment components, the Galactic Cosmic radiation is the least important at the near earth altitudes. (Galactic cosmic radiation becomes important for interplanetary flight considerations due to the higher particle fluxes.) Therefore, the trapped radiation environment and the Solar Flare environment are the most significant from the standpoint of crew protection. From the discussions of Section 6.3.1.2.2, it can be seen that complete shielding of a Base from the solar flare and natural radiation environment is impractical. The solar flare is a significant contributor to the total dose (Reference 6-9) and may exceed the allowable dose to the eye under normal conditions. <u>Protection against solar flares will require a storm shelter particularly for crew durations in excess of one year.</u>

Localized shielding can be used effectively to shield local radiation sources such as on-board isotopes. Optimum materials that would be used for shielding depend on the particle

type and particle energies. The relative effectiveness of various shielding materials in shielding different types of isotope sources which may be carried on-board may be evaluated from the data in Reference 6-10.

Radiation Monitoring. On-board monitoring of the dose received by the crew is important from the standpoint of protecting the crew and maximizing the effectiveness of the crew and identifying radiation hazards.

The previous section alluded to the uncertainty associated with the occurrence and severity of solar flare events. Continuous on-board radiation dose monitoring of personnel would provide timely evaluation of individual crew member dose to allow for planning of extension of tour of duty, e.g., to complete a vital experiment or function, or to allow for participation in emergency activities which would expose him to higher than normal dose rates. In light of the uncertainty in solar flare activity, this would provide for increased mission flexibility and conversely, protect the crew member from early overexposure. On-board monitoring can also indicate violation of procedures or an unsafe condition in the activities of crew members. An individual whose dose level is increasing inordinately in comparison to the rest of the crew can be traced to determine the source of the anomaly.

A second aspect of radiation monitoring is providing early warning of high radiation levels, which not only affect the Space Base in general, but also laboratories which include isotope or dynamic radiation equipment. Section 7.3.1 outlines the elements of such a radiological safety program and indicates the recommended equipment and personnel requirements.

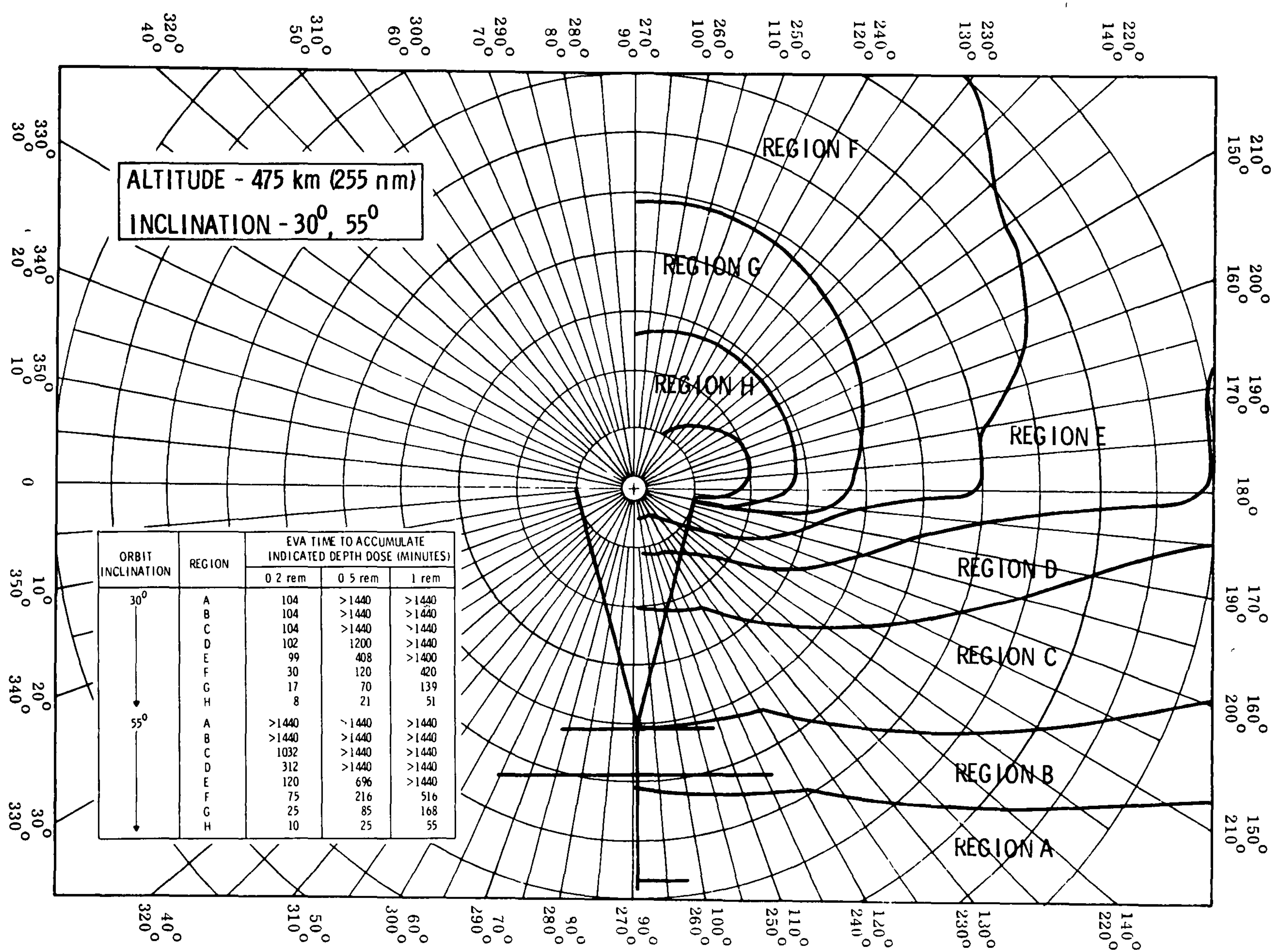
Crew Operations. Table 6-3 lists operational considerations associated with the crew. The necessity to minimize the dose to the crew is emphasized. The guidelines for periodic and career exposure are shown in Section 4.1. Several factors influence the actual dose that a crew member would receive. For a given orbit, these factors include solar activity, crew member work location and function. For example, personnel engaged in EVA may accrue a higher dose over a given period due to exposure to natural radiation with lighter shielding. Similarly, personnel working with isotope sources or on power system

maintenance may also experience higher doses. Therefore, it may not be possible to establish a crew rotation period, without introducing inefficiencies in crew utilization (e.g., the highest dosed crew member would set the maximum rotation period for more lightly affected members). It appears that to maximize crew utilization, actual planning for crew member rotation should rely heavily on the Radiological Safety Program described in Section 7.3.1. Decisions to extend experimentation efforts, rotate reactor operations crew, or assess effects of EVA activity can be based on hard data rather than extrapolations of predicted environments.

The remaining guidelines are associated with rendezvous and EVA associated activity. Due to the high natural environment dose rates encountered in the South Atlantic anomaly, EVA activity should be planned for orbits which do not intercept this region. Similarly, during periods of EVA, the location of the astronaut and the time period at that location should be controlled because of the variation of the radiation field around the reactors. The importance of establishing the local environment before performing EVA cannot be overemphasized.

6.3.1.3 Effects on Subsystems - Normal Radiation Environment

The effects of radiation on the Space Base Subsystems can be segregated into effects on electronic equipments and effects on other spacecraft material. The effects on semi-conductor electronics may be broken down into two types: Bulk damage effect which is the disruption of the crystal lattice and ionization effects which result from interactions of ionized gases with ionized semi-conductor surface impurities. Other subsystem materials react in different manners, ranging from loss of flexibility and outgassing in plastics to insensitive materials such as dry lubricants. (See Section 4.0 and Appendix A for detailed data.)



ORBIT INCLINATION	REGION	EVA TIME TO ACCUMULATE INDICATED DEPTH DOSE (MINUTES) 0.2 rem	0.5 rem	1 rem
30°	A	104	>1440	>1440
	B	104	>1440	>1440
	C	104	>1440	>1440
	D	102	1200	>1440
	E	99	408	>1400
	F	30	120	420
	G	17	70	139
	H	8	21	51
55°	A	>1440	>1440	>1440
	B	>1440	>1440	>1440
	C	1032	>1440	>1440
	D	312	>1440	>1440
	E	120	696	>1440
	F	75	216	516
	G	25	85	168
	H	10	25	55

Figure 6-8. EVA Duration to Accumulate 0.2, 0.5, and 1 Rem Depth Dose Considering Transit through the South Atlantic Anomaly

In evaluating the effects on a Space Base, component definition contained in References 6-7 and 6-11 was used to establish typical subsystem components. The sensitivity of these components to bulk damage or ionizing radiation effects has been broken down into three levels of damage:

- Threshold Damage - Specific effects occur which would likely require some consideration in design to insure proper operation.
- Moderate Damage - Significant degradation of component performance occurs requiring special design considerations.
- Severe Damage - Operation is seriously impaired possibly requiring new design approaches.

Figures 6-9 and 6-10 summarize the sensitivity of the various subsystems. Semi-conductor bulk damage effects have been normalized to the equivalent 1-Mev neutron environment. The 1-Mev neutron effects also include the effects on materials of secondary ionizing radiation produced by neutrons. The ionization effects includes the effect of all particles on both materials and electronics. Figures 6-11 and 6-12 present a more detailed breakdown of the subsystems by component.

In each of these figures the total radiation dose to which the subsystems would be exposed in a 10-year mission has been superimposed on the sensitivity charts. The reactor contribution to this dose is shown by the dotted line and is seen to be negligible compared to the natural radiation environment. The natural environment dose was computed for a range of possible effective shielding (1 to 10 g/cm^2)and, therefore, covers both the equipments on the Space Base as well as those on experiment module subsatellites.

As can be seen from Figure 6-9 and 6-10, the radiation exposure of the subsystems cannot be neglected as each subsystem contains some components that exhibit at least threshold sensitivity to the projected environment. Therefore, specific design considerations must be implemented for these components in order to insure proper operation. <u>Neglecting film and experiment interference considerations, the radiation effects on the subsystems,</u>

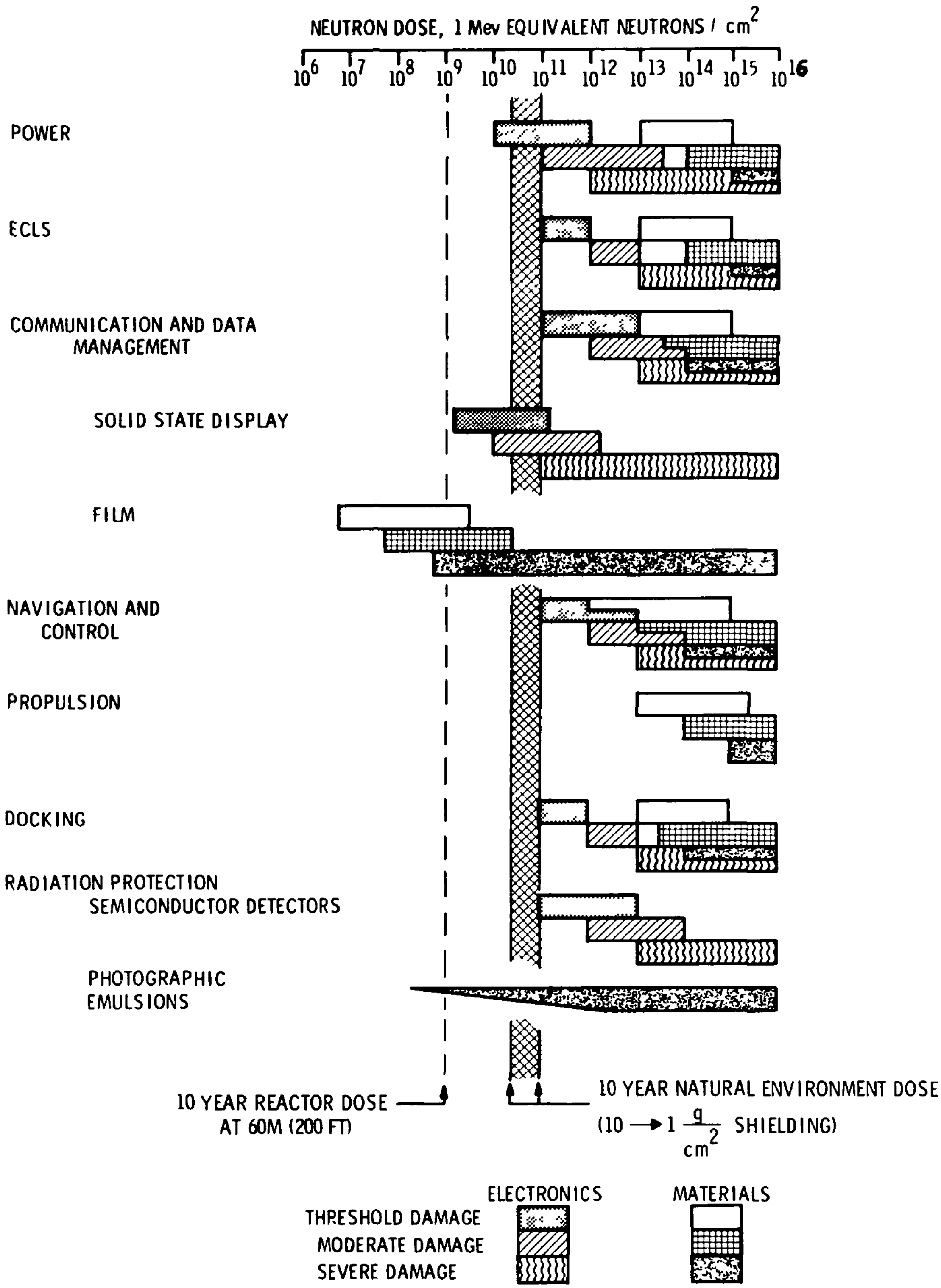


Figure 6-9. Summary of 1 MEV Neutron Effects in the Space Base Support Subsystem

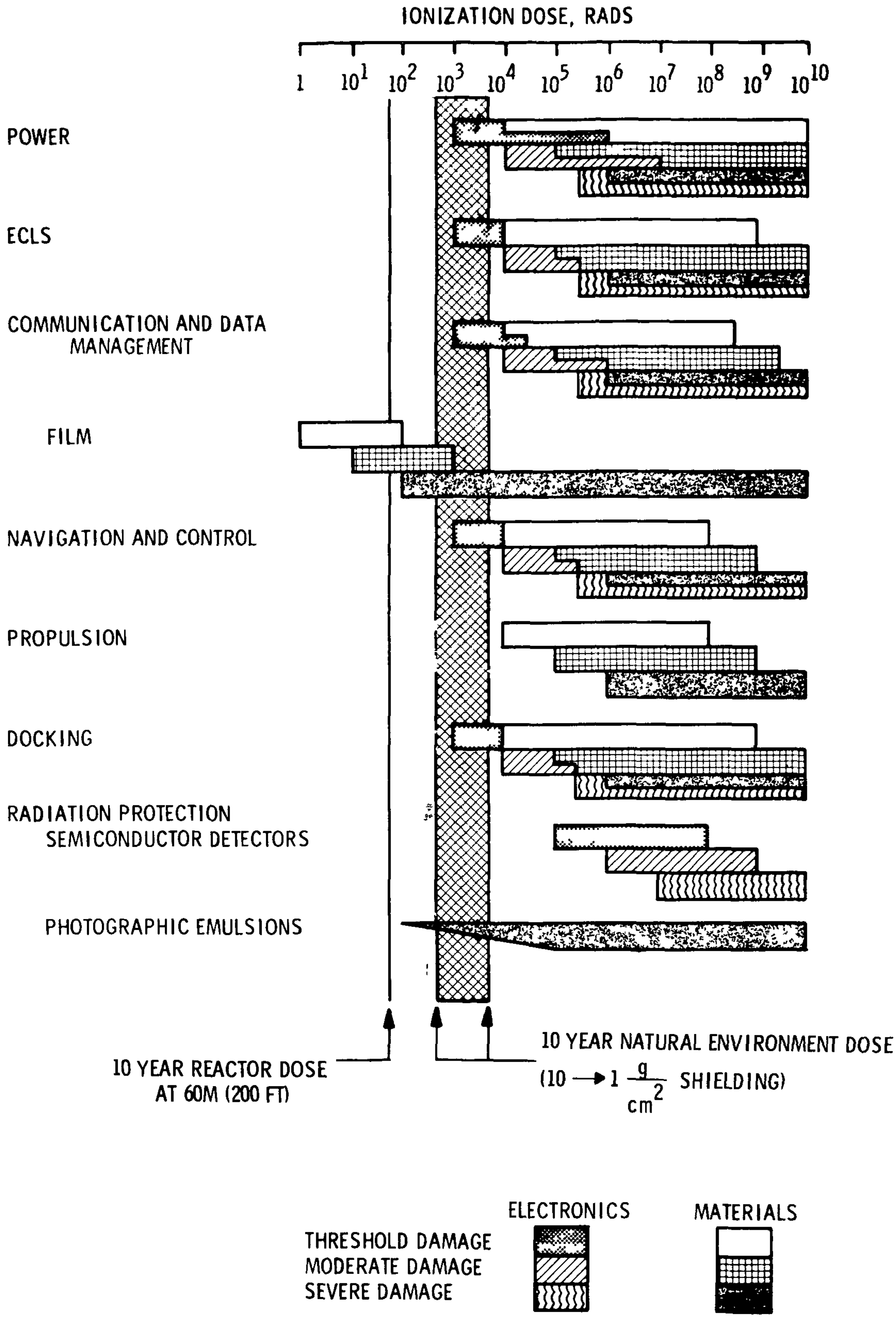


Figure 6-10. Summary of Ionization Effects in the Space Base Support System

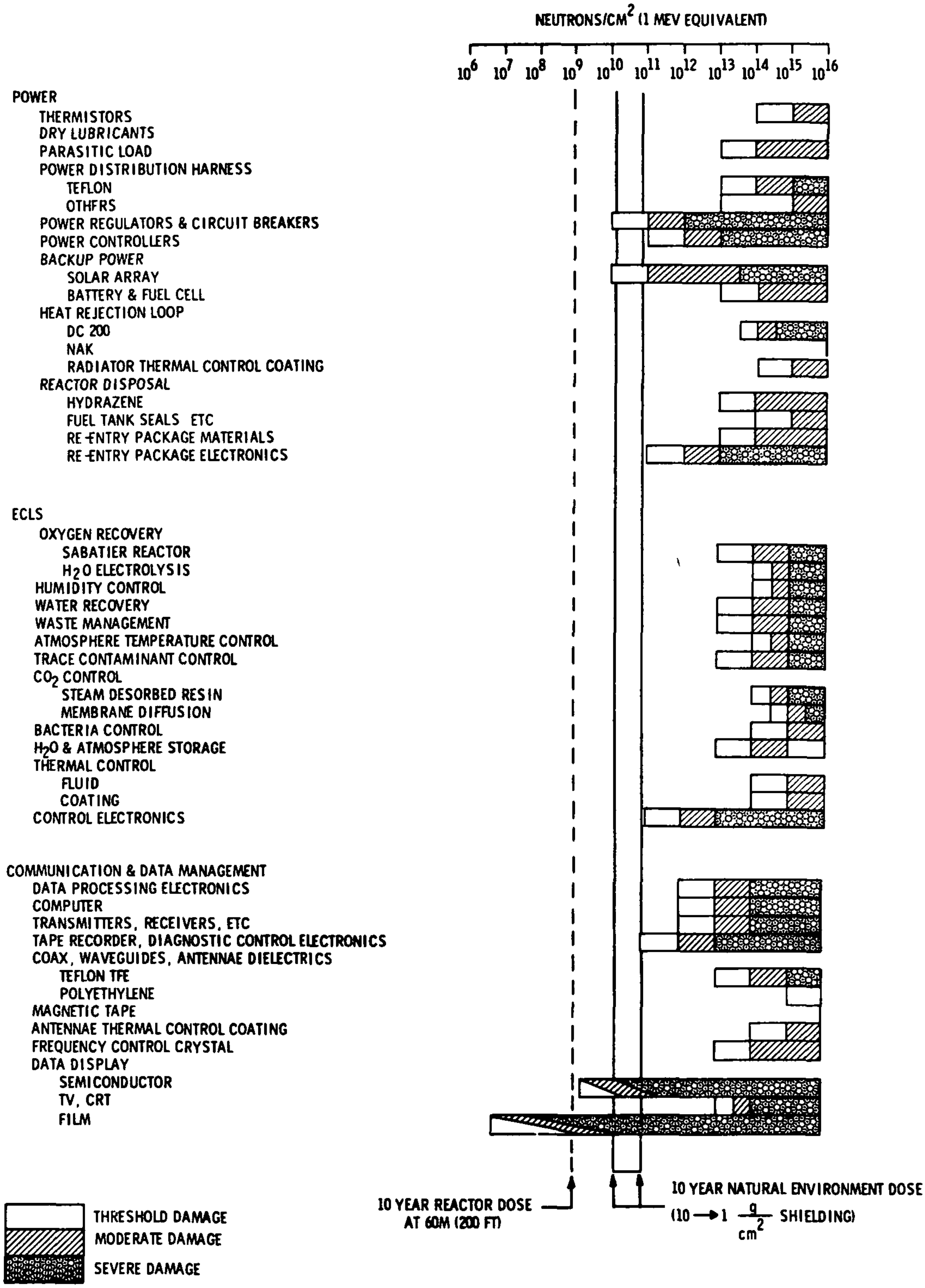


Figure 6-11. 1 MEV Neutron Effects Space Base Support Subsystem Components

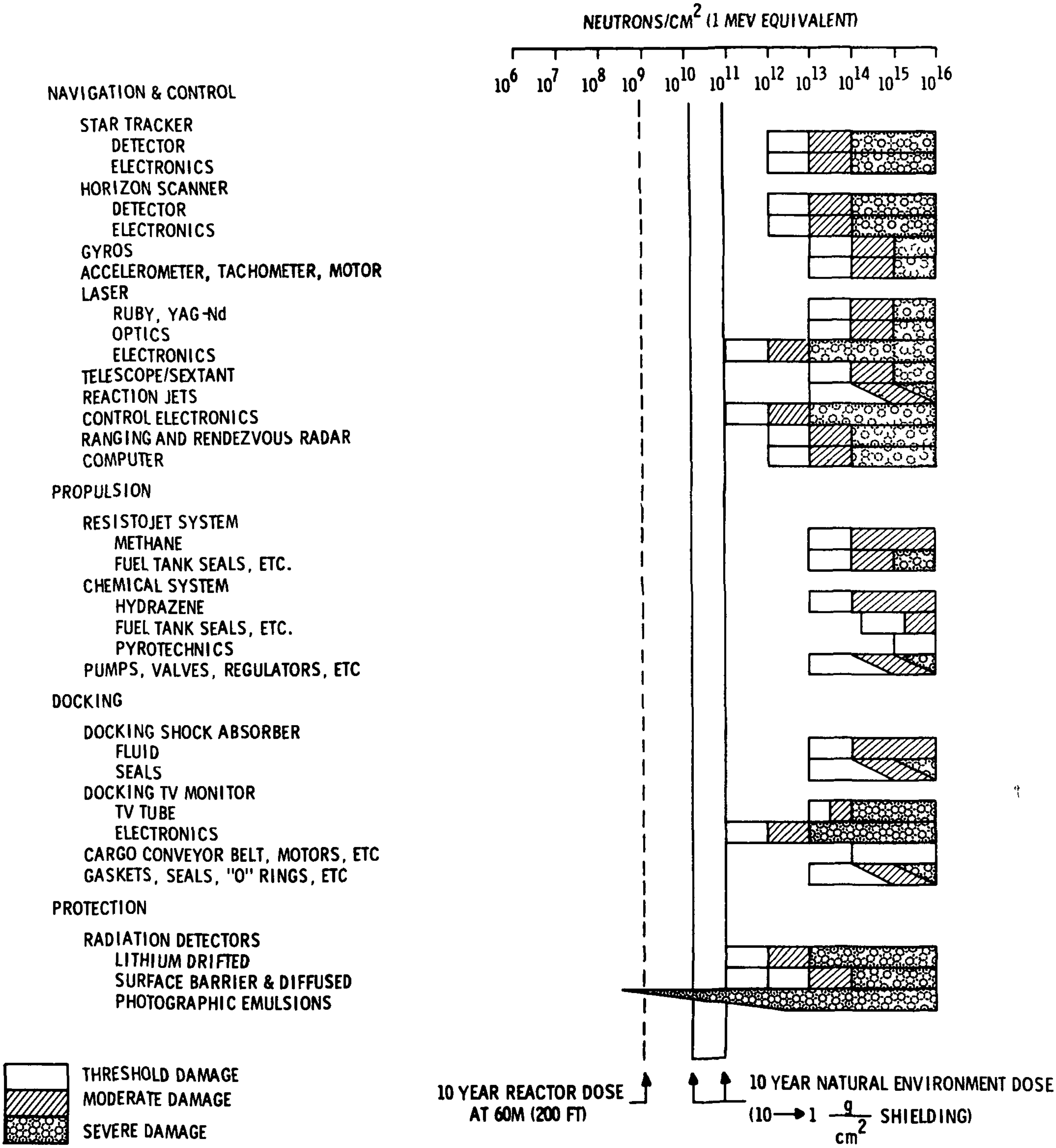


Figure 6-11. 1 MEV Neutron Effects Space Base Support Subsystem Components (Cont)

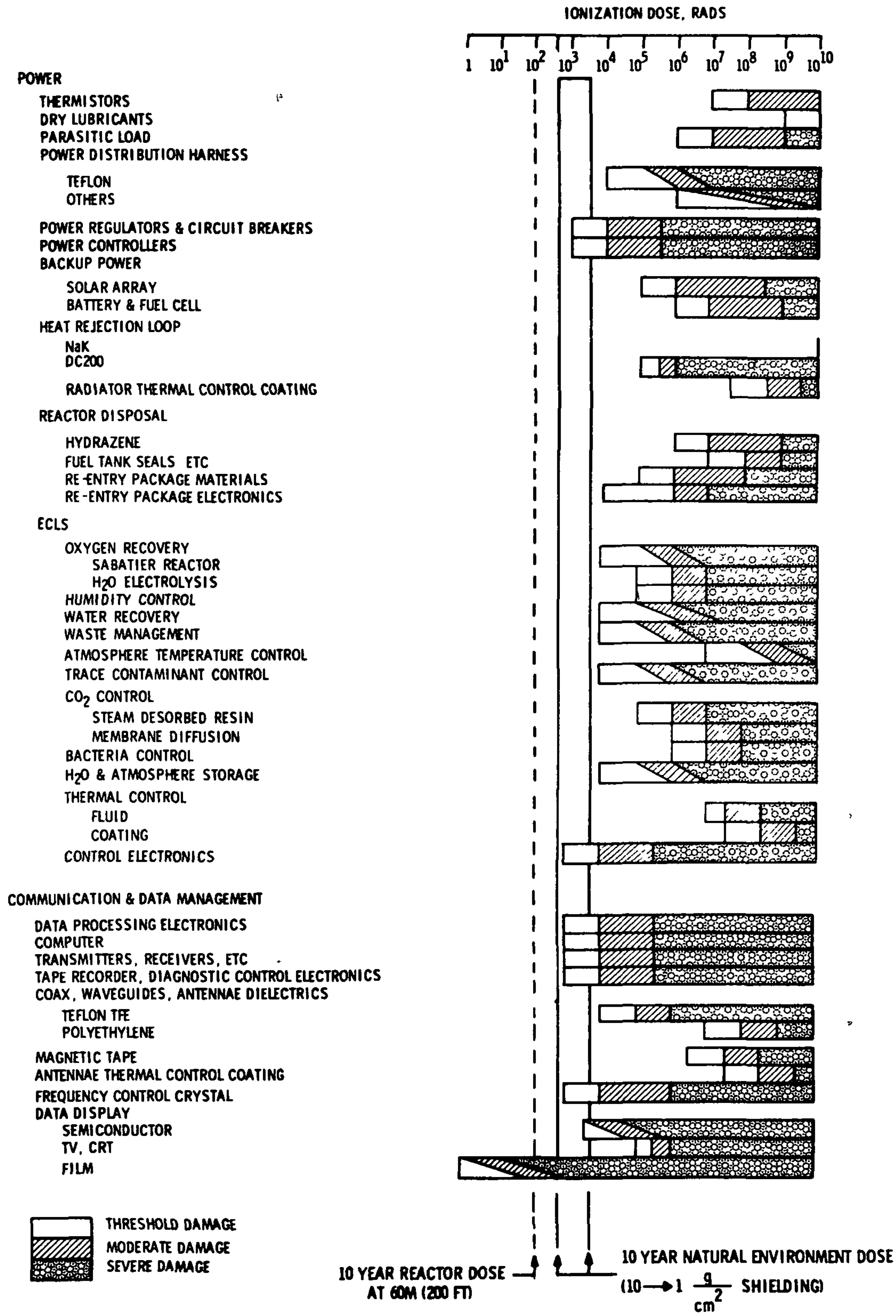


Figure 6-12. Ionization Effects, Space Base Support Subsystem Components

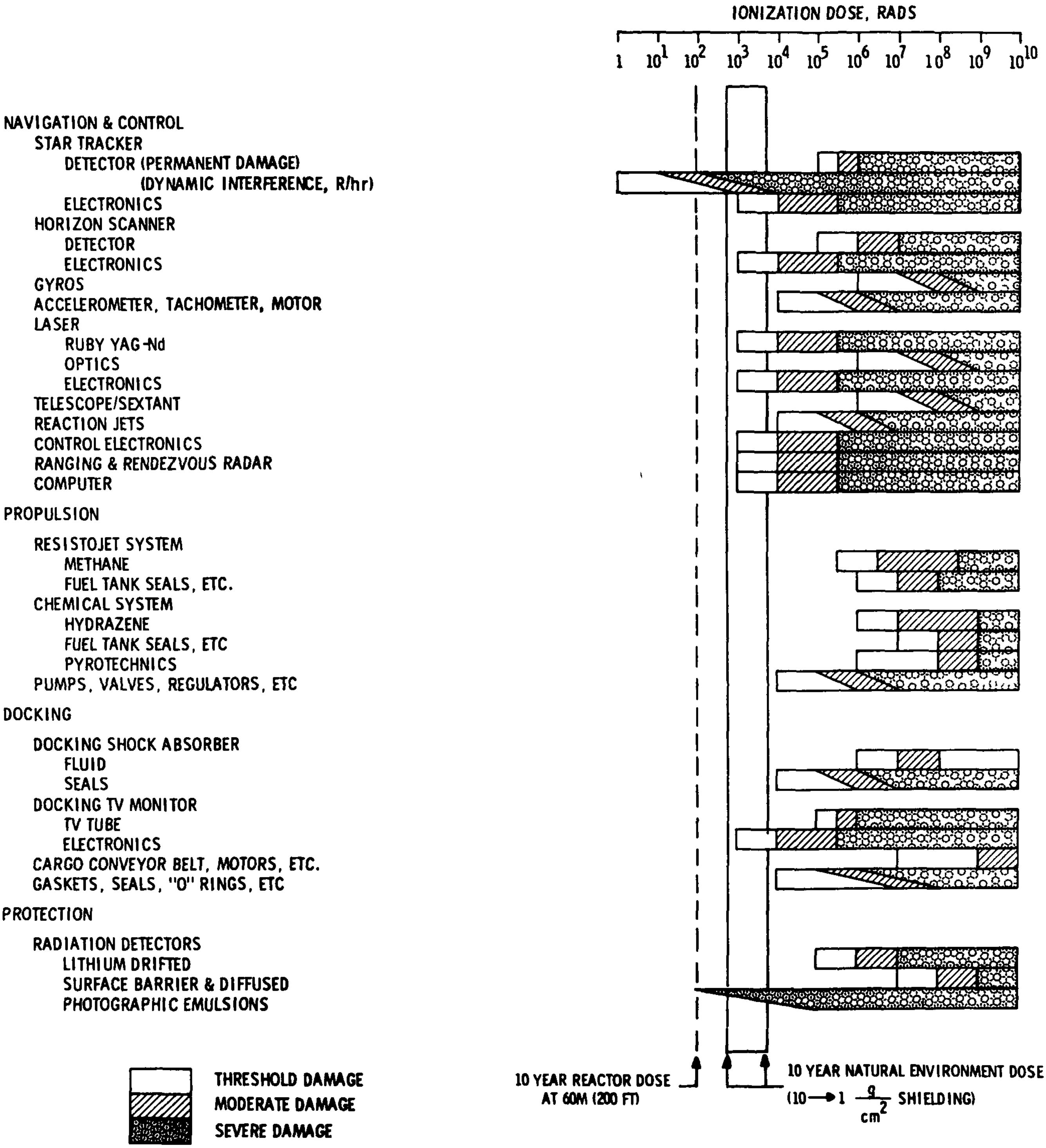


Figure 6-12. Ionization Effects, Space Base Support Subsystem Components (Cont)

during a 10-year mission, are considered to constitute a negligible hazard providing piece parts and materials are judiciously selected during the design process. (See Appendix A, Radiation Exposure Limits, for projections of component hardening capability).

Since photographic film is primarily associated with the Space Base experiment program, film considerations as well as experiment interference are discussed in Section 6.3.1.4.

6.3.1.3.1 Subsystem Design and Operational Considerations

This section deals specifically with typical Space Base subsystems exclusive of the Reactor Power Modules. Table 6-4 lists the subsystem design and operational considerations arising from the nuclear hazards during orbital operations. The subsystem nomenclature follows the definition presented in Section 3.2.2.2.

The analyses (Section 6.3.1.3) indicate that equipment associated with expected subsystem implementation may be marginal in terms of degradation due to the combined radiation environment. Therefore, component and subsystem design should reflect this condition and employ hardening techniques where required. Particular subsystem considerations are discussed below.

Navigation and Control - The design considerations of interest specifically to the Navigation and Control System deal primarily with sensors and propulsion capability. Star trackers may be one of the few subsystem components that may be sensitive to high dose rates. These dose rates could result from the natural environment (solar flares) or could be caused by accident situations (such as a reactor power excursion). The susceptibility to these environments could result in temporary loss of attitude reference during critical maneuvers.

A nuclear related hazard, thermal interference from high temperature waste heat radiators, should also be considered. If IR scanners are incorporated in the attitude control of such interfacing vehicles as the Tug, Shuttle, or detached experiment modules, a false signal could be generated during critical rendezvous maneuvers.

Table 6-4. Support Subsystem Design and Operations Guidelines

DESIGN

GENERAL

- Select components and component piece parts to minimize degradation due to radiation exposure over the mission duration

NAVIGATION AND CONTROL

- Screen dose rate sensitive equipment to eliminate catastrophic interference from high radiation levels during normal operations or accident conditions
- *Consider susceptibility of IR scanners on interfacing vehicles to false signals from waste heat radiators*
- Consider providing sufficient orbit adjust capability to rapidly change Space Base orbit altitude

COMMUNICATIONS AND DATA MANAGEMENT

- Provide capability and interfaces with on-board Radiological Safety Program for radiation dose data handling

ENVIRONMENTAL CONTROL AND LIFE SUPPORT

- Provide separate waste management systems for crew and laboratory contaminated waste
- Provide separate atmosphere control for laboratories with high concentrations of isotope in use or in storage
- Provide radiation shielding for isotope powered waste management systems
- Consider locating isotope powered waste management systems in areas of low traffic which are not continuously occupied by a specific individual(s)
- Consider using strippable thermal control coatings on vehicle exterior surfaces for long term maintainability and as a means of NaK or fission product decontamination

STRUCTURES

- Provide capability to isolate compartments containing a high concentration of isotopes
- Consider coating the surfaces of pressure hulls and structure to assure compatibility with NaK coolants

PROTECTION

- Provide means for monitoring and warning of imminent collisions with space debris and orbiting vehicles
- Provide emergency EVA suits which are compatible with NaK, for emergency EVA and PM servicing

OPERATIONS

- Minimize loiter and traverse near reactor to reduce potential radiation and thermal interference with navigational equipment

The analyses of accident conditions Section 6.2.2 and 6.3.2 indicate the severity of the hazard which would result from the release of radioactive debris (e.g., from a destructive reactor excursion) that would have a long residence time in the vicinity of the Space Base. A possible approach to minimizing the hazard is to remove the Space Base from the vicinity (orbit) of the debris. The penalty associated with implementing this capability depends on the quantity of debris released and the expected dispersion. Since the dose rate is approximately proportional to the inverse of the square of the separation distance a relatively small mass/logistic penalty may significantly enhance safety.

Communications and Data Management - Due to the large quantity of electronics associated with this subsystem, the selection of radiation hardened piece parts and components is particularly applicable. Specifically, semi-conductor data displays may exhibit some degradation from long term exposure to the general radiation environment. (Figures 6-9, 6-10, 6-11 and 6-12).

In addition, the communications subsystem must allow for equipment interfaces and data handling associated with the radiological safety program (see Section 7.3.1). This is especially important since recognition of these requirements in early phases of design will allow for the capacity and flexibility required.

Environmental Control and Life Support (ECLS) - The considerations associated with the ECLS subsystem stem primarily from the use of isotopes internal to the Space Base.

A portion of the experimentation aboard the Space Base is expected to use isotope tracers, both in Space Manufacturing and the Biosciences. Contaminated waste from these laboratories (biological specimens, solutions) must be segregated from the general waste management system. This precaution is necessary not only to safeguard against consumption of excess quantities of isotope, but also to eliminate the dissemination of isotopes that could interfere with subsequent experimentation. Depending on the quantity of isotopes (tracers of capsules) stored in a given area, a spill or capsule leakage could spread excessive quantities of radioactive material throughout the Space Base (see Section 7.3.2). Environmental isolation is required.

The implementation of isotope powered waste management systems can significantly perturb the radiation environment in areas immediately adjacent to the system's location. Localized shielding may be required. In addition, it is undesirable to locate these systems in or near areas that would be subject to continuous or high percentage occupancy by a specific individual(s) in order to minimize the radiation dose.

Structures - The considerations dealing with the structures and docking and airlock subsystems arise from the release of isotope contamination within the Space Base and corrosive material (NaK) external to the Space Base. Airlock/compartment closure provides assurance that the airborne and entrained contamination that could arise from compartments containing isotope inventories could be minimized effectively in the event of a release.

NaK coolant release effects on the structure must be considered. Compatibility between aluminum and aluminum alloys has been reported up to 500°K. Coolant from the primary loop is significantly above this temperature (945°K) and therefore there exists the possibility of contact between the structure and NaK coolant at temperatures above compatibility levels for a period of time dependent on the quantity released. This accident situation is discussed in Section 6.3.2.1.2. In recognition of this situation, provision for NaK compatible coating materials in the vehicle structure has been recommended.

Protection - The protection subsystem comprises crew habitation modules, living quarters, IVA and EVA suits, etc. Activated and corrosive NaK can reduce or eliminate protective subsystem effectiveness and thereby present a hazard. From the standpoint of radiological hazards, collision with large pieces of space debris or orbiting vehicles can also induce failures resulting in NaK coolant release, loss of reactor control, etc., (see Appendix C). These types of accident situations are addressed in Section 6.3.2.1. The severity of the effects of such a collision are sufficient that positive means should be employed to avoid such a condition. Advance warnings combined with an orbital adjust capability could provide the means for collision avoidance.

Two conditions that could require special crew protection during emergency operations in the presence of NaK are: (1) a NaK coolant leak external to the Space Base (Section 6.3.2.1), and (2) a leak in the Power Conversion equipment engine room (see Section 7.3.3). In such circumstances it may be desirable to provide access to these regions to accomplish "safing" of the system or rescue operations. The provision of an EVA suit which is compatible with NaK should be a design objective.

6.3.1.4 Effects on Experiments (Normal Radiation Environment)

In evaluating the effect of potential radiological hazards on the experiment program, the data from Section 6.3.1.3 may be applied directly to experiment support equipment from the standpoint of equipment damage. However, radiation interference with measurements and radiological effects on biological experiment specimens must be evaluated separately.

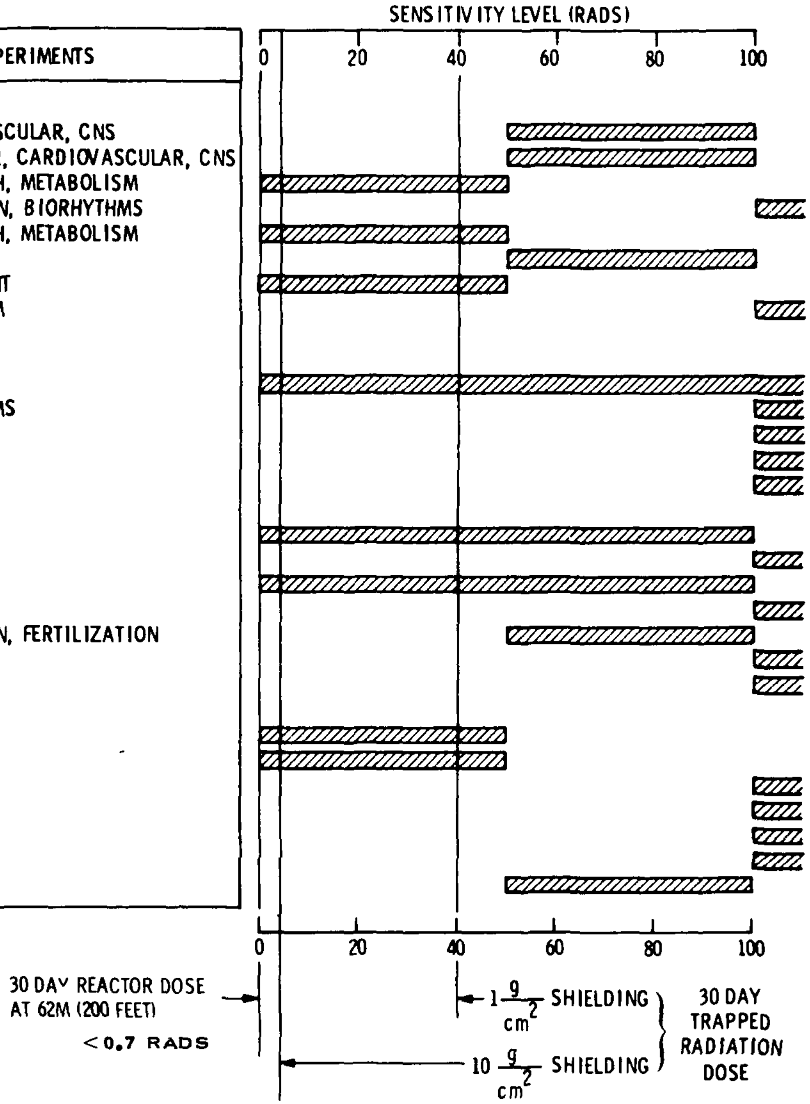
6.3.1.4.1 Bioscience Experimentation.

The Space Base bioscience experimentation program is expected to incorporate a wide range of specimens, including animals, plants and microbiological specimens. Table 6-5 lists examples of candidate experiments and specimens derived from the OMSF publication, "Candidate Experiment Program for Planned Space Stations," (Reference 6-12). As can be seen from this table, there exists a wide range of sensitivity for the various experiments and specimens which depend on the objectives of the experiment and the characteristics of the specimens. Depending on the specimen, radiation sensitivity may be related to age or stage in development. Included in Table 6-5 are the expected doses to which the experiments would be exposed, including both the contribution of the reactor power system and the geomagnetically trapped radiation environment. The occurrence of a solar flare would result in an additional dose of from 3 to 60 rem depending on the effective shielding (10 g/cm^2 to 1 g/cm^2, respectively). The predominant effect is due to the natural environment and, therefore, selection of location within the Space Base in order to minimize reactor dose contribution would have a relatively minor effect on experiment exposure.

In planning experimentation programs it is necessary to evaluate the radiation sensitivity of the specimens to be employed to determine requirements for localized shielding. In addition, particularly sensitive experiments should be equipped with local radiation monitoring

Table 6-5. Bioscience Experiment Radiation Sensitivity

EXPERIMENT CATEGORY	SPECIMEN	TYPICAL EXPERIMENTS
ANIMALS	VERTEBRATES	
	CHIMPS	METABOLISM, CARDIOVASCULAR, CNS
	MONKEYS	METABOLISM, BEHAVIOUR, CARDIOVASCULAR, CNS
	RATS	EMBRYOGENESIS, GROWTH, METABOLISM
		BEHAVIOUR, CIRCULATION, BIORHYTHMS
	MICE, HAMSTERS, RABBITS	EMBRYOGENESIS, GROWTH, METABOLISM
	MARMOTS	IMMUNE RESPONSE
	FROGS	EMBRYO AND DEVELOPMENT
	TURTLES	GROWTH AND METABOLISM
	INVERTEBRATES	
	FRUIT FLY	LIFE CYCLE, GENETICS
		METABOLISM, BIORHYTHMS
	HOUSE FLY	AGING
	FLOUR BEETLE	MOIPHOGENESIS
	BEES AND SPIDERS	BEHAVIOUR
PLANTS	WHEAT	GROWTH
		METABOLISM AUXIN
	PEA	GROWTH
	ARABADOPSIS	DEVELOPMENT
	P. LONGFOLIA	METABOLISM, MORPHOGEN, FERTILIZATION
	CUCUMBER	LIGNIFICATION
	PINTO BEAN	BIORHYTHM
MICROBIOLOGICAL	VERTEBRATES	TISSUE FUNCTION
	AVIAN	EMBRYO DEVELOPMENT
	VIRUS BACTERIA	HOST PARASITE
	FUNGI	BIORHYTHM
	CELL	CELLULAR FUNCTION
		METABOLISM
	GENES	GENETIC STABILIZATION



RADIATION PROTECTION
REQUIRED IS DEPENDENT ON
EXPERIMENT OBJECTIVE

to allow screening of anomalous behavior. The following broad (general) criteria can be used if no previous radiation studies have been performed:

- Warm blooded animals are more sensitive than cold blooded animals.
- Vertebrates are more sensitive than invertebrates.
- Sublethal doses are generally limiting.
- The age of the specimen is critical as to its sensitivity. In life cycle studies, embryos are much more sensitive than adult specimens.
- The larger the chromosome volume, the more sensitive the organism is to radiation.
- Specimens having high cellular division rates (such a embryos, blood, etc.) are highly sensitive to radiation whereas experiments involving low division rates such as muscle, nerve, bone, etc., are least sensitive.

In order to evaluate the sensitivity of experiments to the environments to be encountered on the Space Base, 60 experiments in 8 experimental disciplines (astronomy, physics, etc.) were evaluated. Figure 6-13 shows a summary for equipments associated with the Astronomy experimentation program. Radiation flux rates which would cause data degradation (dynamic interference) are shown for the different particles involved. Permanent damage thresholds for the equipment are also noted. Complete charts for the entire experiment program are given in Appendix A. The analysis allows evaluation of the susceptibility of experiments to both the natural environment and the reactor environment.

Figures 6-14 through 6-19 indicate those areas of the 500 km orbit where dynamic interference would be encountered. These figures are arranged in order of increasing sensitivity, and the degree of interference to be expected is noted for the applicable experiments. In each figure, the large area of sensitivity near the center indicates the influence of the South Atlantic anomaly. As can be seen, several experiments would have to be turned off or data ignored during passage through these areas, unless special shielding or measurement techniques are provided.

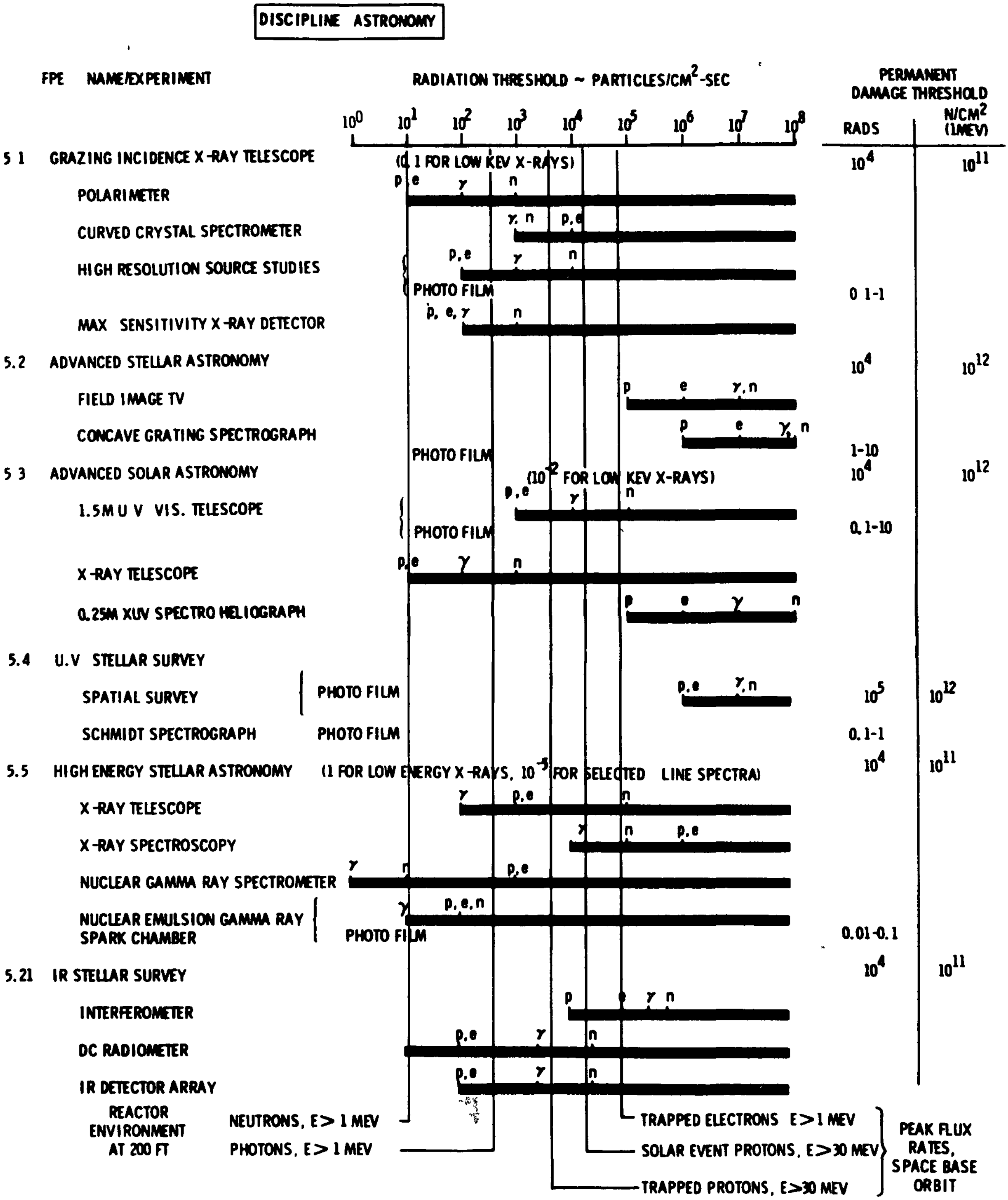
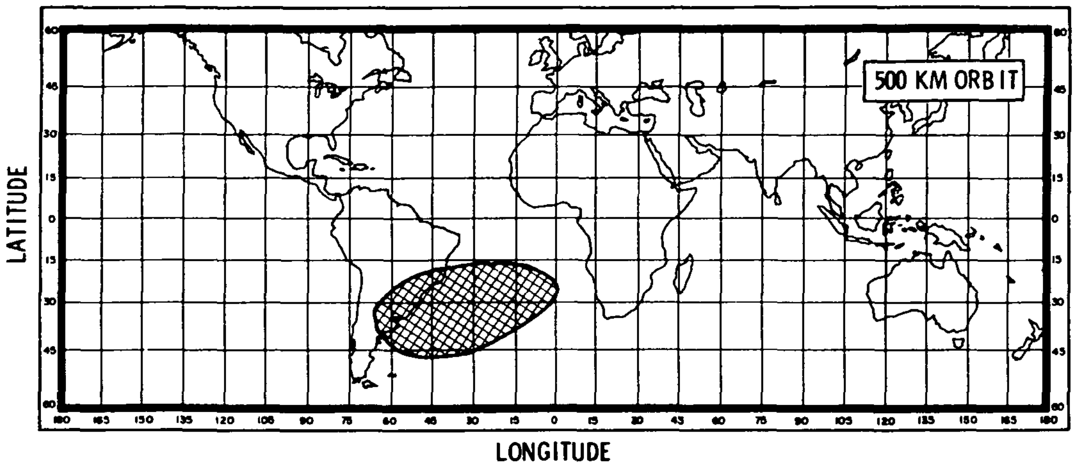


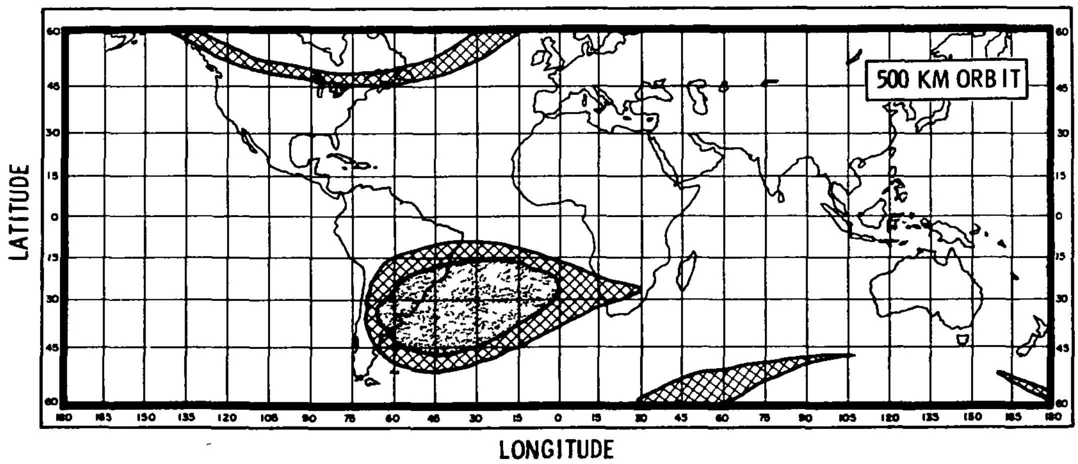
Figure 6-13. Experiment Radiation Sensitivity Thresholds



FPE 5.1 - GRAZING INC. X-RAY TELESCOPE CURVED XTAL SPECT
5 6 - ENVIRONMENTAL COMPOSITION
5 17 - CONTAMINATION MEASUREMENTS CLOUD COMPOSITION
5.24 - ENGINEERING OPERATIONS OPTICAL RADAR

THRESHOLD EFFECTS S/N = 10
SEVERE EFFECTS S/N = 1

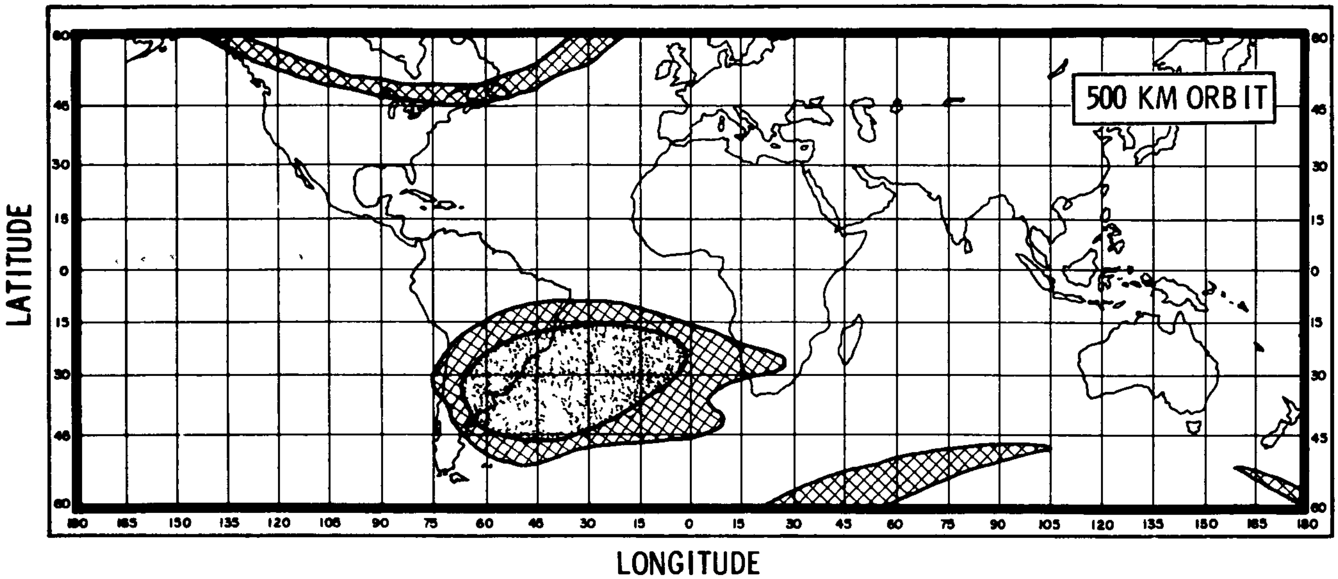
Figure 6-14. Orbit Contours for Dynamic Interference in Experiments



FPE 5.3 - ADVANCED STELLAR AST 1.5m U V VIS TELESCOPE
5.5 - HIGH ENERGY STELLAR AST X-RAY TELESCOPE
NUC RAY SPECT
5.6 - SPACE PHYSICS AIRLOCK EXP: CONTAMINATION MEAS
5.11 - EARTH SURVEYS· MULTISPECTRAL IR SCANNER
VISIBLE WAVELENGTH POLARIMETER
5.24 - ENGINEERING & OPERATIONS: GUIDANCE
: LASER COMMUNICATION
5.26 - INVERTEBRATES

THRESHOLD EFFECTS S/N = 10
SEVERE EFFECTS S/N = 1

Figure 6-15. Orbit Contours for Dynamic Interference in Experiments

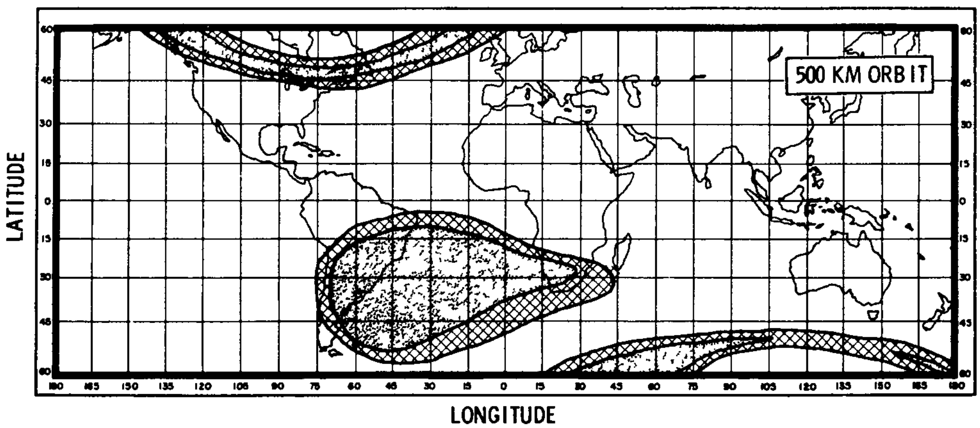


FPE 5.22 - COMPONENT TEST & SENSOR
CALIBRATION: MICROWAVE
: LWIR

THRESHOLD EFFECTS S/N = 10

SEVERE EFFECTS S/N = 1

Figure 6-16. Orbit Contours for Dynamic Interference in Experiments



FPE 5.1 - GRAZING INC X-RAY TELESCOPE HR SOURCE STUDIES
· MAX. SENS. X-RAY DETECT
5.5 - HIGH ENERGY STELLAR ASTRON NUC EMUL
X-RAY SPARK CHMB.
5.6 - SPACE PHYSICS AIRLOCK EXP GEGENSHEIN/
ZODIACAL LIGHT
5.7 - PLASMA PHYSICS & ENV PERT · ACCELERATOR
EXP.
5.8 - COSMIC RAY PHYSICS LAB. INTERACTION
PHYSICS
5.21 - IR STELLAR SURVEY DC RADIOMETER
IR DETECTOR ARRAY

THRESHOLD EFFECTS S/N = 10

SEVERE EFFECTS S/N = 1

Figure 6-17. Orbit Contours for Dynamic Interference in Experiments

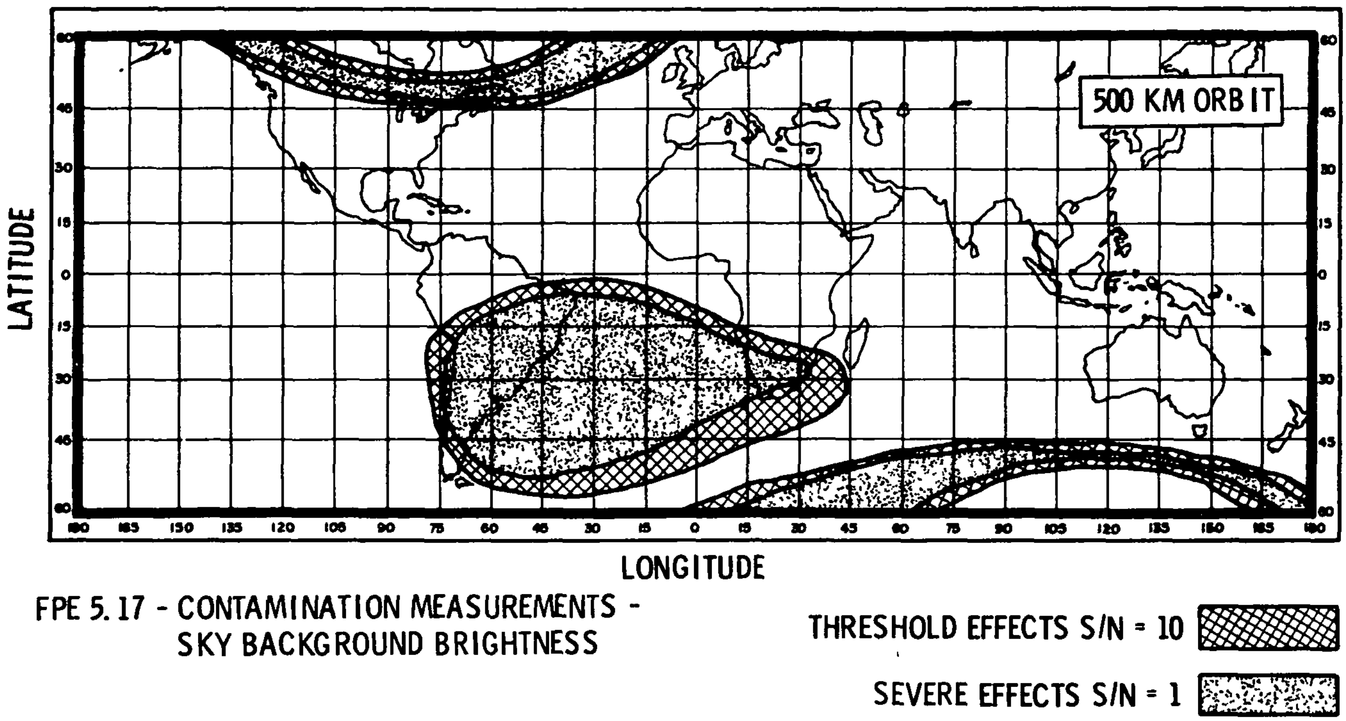


Figure 6-18. Orbit Contours for Dynamic Interference in Experiments

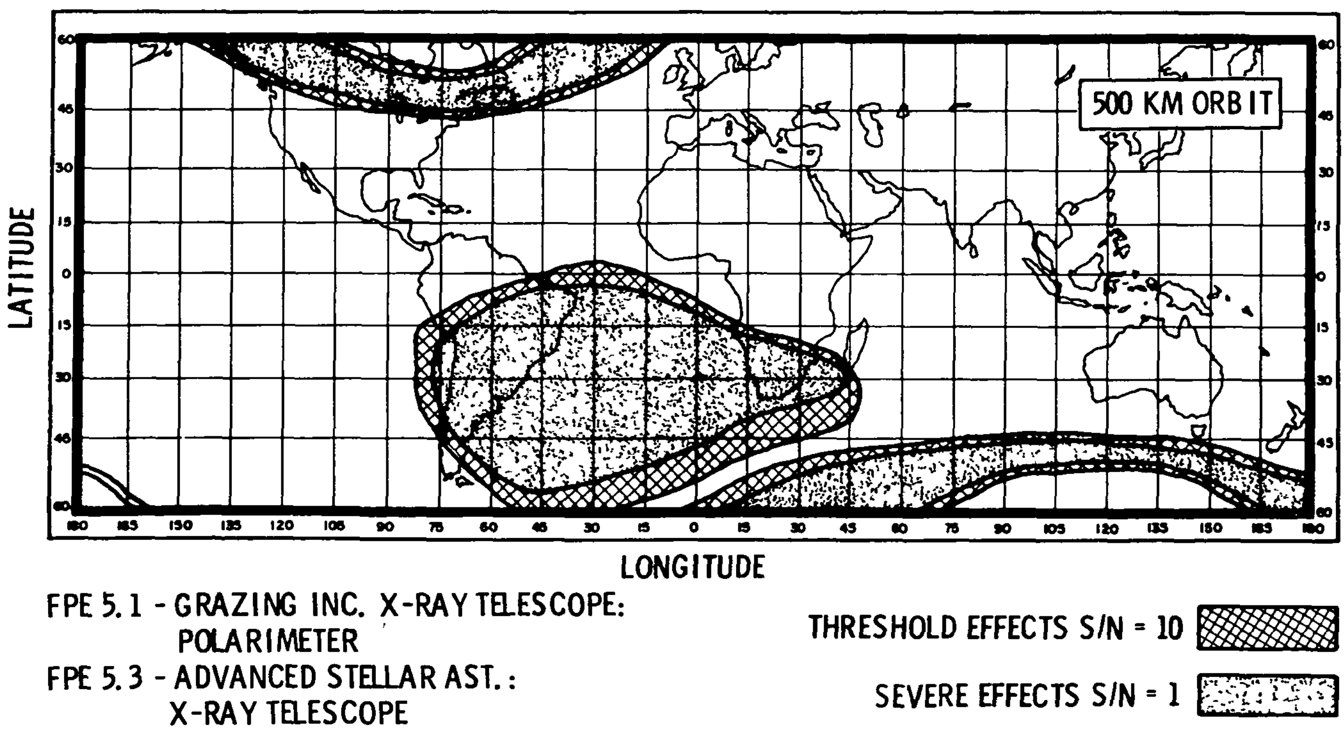


Figure 6-19. Orbit Contours for Dynamic Interference in Experiments

Whereas the preceding figures indicate the sensitivity to the natural environment (primarily trapped electrons and protons) experiments also exhibit sensitivity to the neutron and gamma ray environment induced by the reactors. To avoid dynamic interference from the reactors, Figure 6-20 indicates the minimum approach distances to the Space Base reactors for various operating experiments which are candidates for implementation as subsatellites (detached or free-flying modules). These distances are in relation to the lightest shielded area of the reactor, as shown in the figure. If Space Base orientation were to be managed, closer approaches would be allowable, i. e., from the more heavily shielded directions.

6.3.1.4.3 Photographic Film Degradation

The photographic film associated with the experiments requires special handling in order to minimize data degradation. Figure 6-21 shows the sensitivity of film stored on the Space Base. The threshold of fogging is defined as the exposure which would result in a film optical density of 0.2 (see Appendix A, Section A.3). From Figure 6-21 it is apparent that even assuming a shielded storage facility (20 g/cm^2), careful handling of the film is required. Specifically, film should be used as quickly as possible and developed immediately after use. This procedure would maximize the film usefulness, however, resupply would be

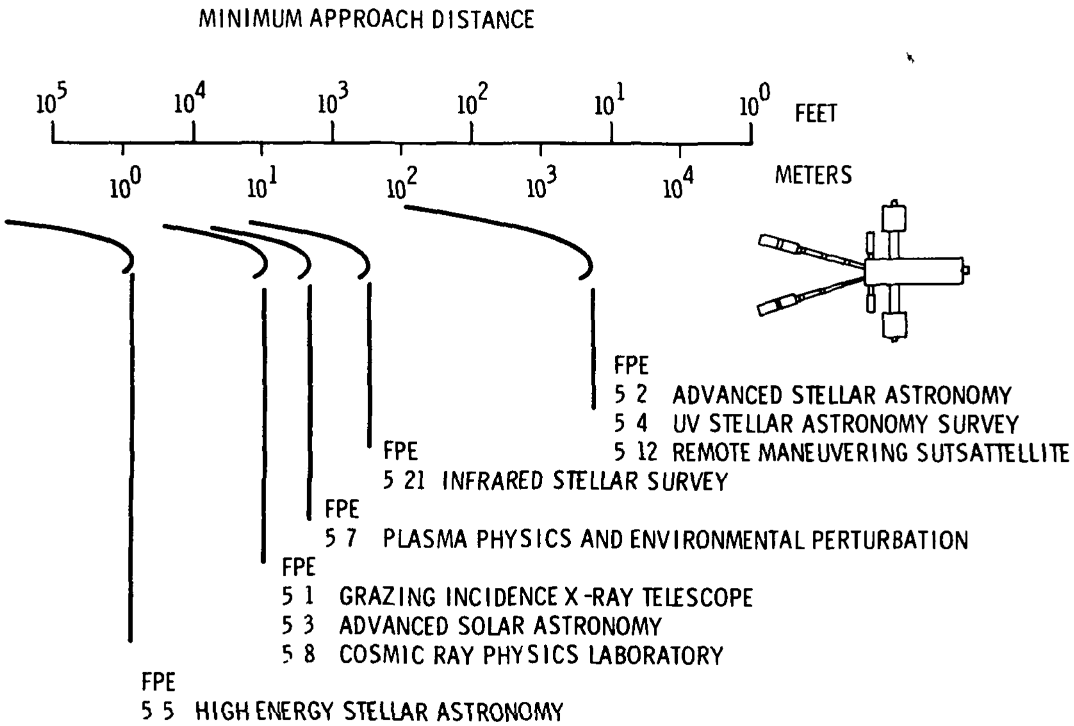


Figure 6-20. Detached Module Dynamic Interference

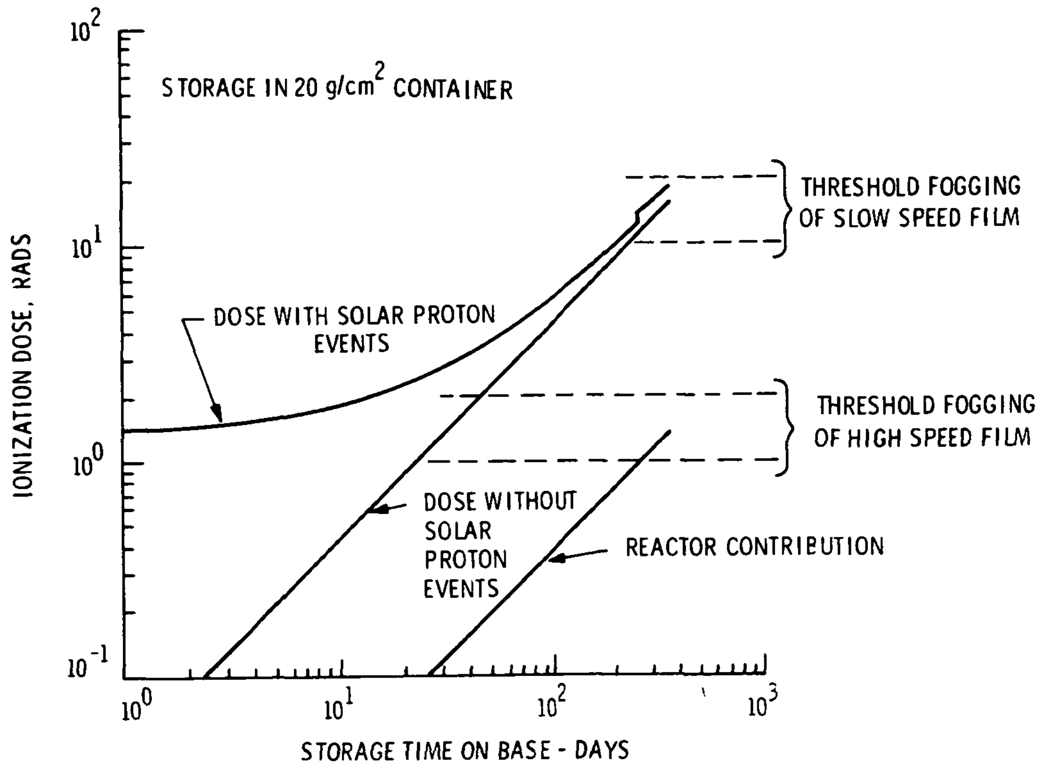


Figure 6-21. Space Base Photographic Film Considerations

required on a regular basis. Depending on the acceptability of the optical density of 0.2 as a fog threshold, fast film (ASA400-800) would have to be resupplied every 25 to 50 days. In addition, the occurrence of a solar flare during the storage period could require complete resupply of the film inventory. To aid on-board evaluation of film acceptability, dosimeters could be included with the stored film jackets to allow correlation of fogged condition for the particular type of film.

In addition to film used on the Space Base, detached experiment modules will also employ film. This film may be exposed to a slightly higher radiation environment than that stored on the Base since less shielding will be provided by the vehicle structure and also since there exists the possibility of exposure to the lightly shielded area of the reactor. Figure 6-22 shows film sensitivity as a function of time at distance from the lightly shielded area of the reactors, for different film shielding conditions (10 to 20 g/cm^2). As separation distance from the reactors increases, the storage time that produces threshold fogging is eventually limited by the natural environment (assuming no solar flare). Although initial

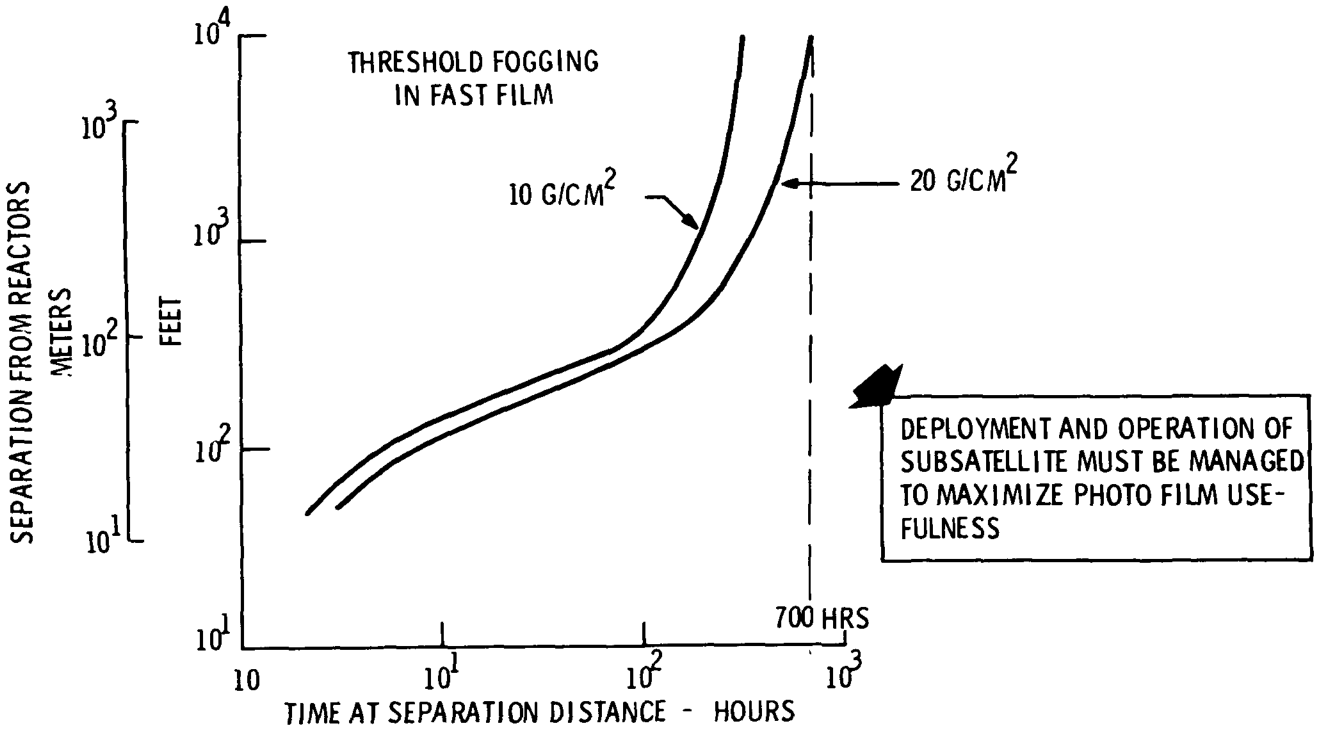


Figure 6-22. Detached Module Photographic Film Constraints

visual observation of the detached module might be desirable in order to verify operation, deployment trajectory and operational location must be managed in relation to the reactors to maximize film usefulness.

6.3.1.4.4 Experiment Design and Operational Considerations

Table 6-6 presents design and operational guidelines dealing with the implementation of the Space Base experiment program. The guidelines listed have been grouped according to the associated hazard source.

Design for General Radiation Environment - In discussing subsystem design considerations, in Section 6.3.1.3.1, the requirement for designing to survive the general radiation environment was noted. However, the required design life of the experiment should be evaluated in order to determine whether special design implementation is actually required.

Film associated with the experiment program is one of the most sensitive elements of the Space Base Program. Analyses indicates that when stored in a shielded container (20 g/cm^2), high speed (ASA 400-800) film would have a life of 25 to 50 days depending on film speed. In order

Table 6-6. Experiment Program Design and Operations Guidelines

DESIGN

GENERAL RADIATION ENVIRONMENT

- Provide hardening of electronics associated with experiment equipments expected to be in long term usage
- Provide shielded storage for photographic film and emulsions
- Consider storing dosimeters in on-board film storage areas to allow evaluation of fog condition and film acceptability
- Monitor radiation dose to radiation sensitive bioscience experiment specimens
- Design for radiation screening to reduce dynamic interference in experiments taking measurements within environmental radiation regimes (e g , anti-coincidence techniques)

GAMMA AND NEUTRON ENVIRONMENT

- Provide for detached module (subsatellite) implementation of gamma ray and neutron sensitive experiments (e g , FPE 5 1, 5 5)
- Maintain neutron and gamma sensitive experiments within the shadow shielding of the reactors, if attached or integral with the Space Base (e g , FPE 5 7, 5 17)

DYNAMIC GENERATOR ENVIRONMENT

- Provide shielding and interlocks, and restrict reorientation and relocation of dynamic generators (x-rays, ion guns, lasers and microwave sources)

ON-BOARD ISOTOPE ENVIRONMENT

- Provide secure, unbreakable storage of isotope (tracers and capsules) both in launch and operational configurations
- Establish laboratory protection equipment (filters, detectors, glove boxes, airlocks, etc) consistent with the type and quantity of isotope and tracers likely to be used in a given laboratory
- Provide thermal shielding to protect personnel from high temperature isotope capsules
- Consider locating laboratories using isotope tracers, in zero-g portions of the vehicle in order to preclude contamination (spills) resulting from the loss of artificial "g" capability
- Consider locating laboratories with high tracer and isotope concentrations, in isolatable, removable modules to preclude general internal contamination of large permanent portions of the Space Base

OPERATIONS

GENERAL RADIATION ENVIRONMENT

- Consider curtailing experiment operation through major portions of the South Atlantic Anomaly and portions of the polar regions to prevent dynamic interference/data degradation (e g , FPE 5 1, 3, 5, 6, 7, 8, 11, 17, 21, 22, 24, 26)
- Provide experiment data screening procedures for experiments sensitive to South Atlantic Anomaly interference
- Provide regular resupply of photographic film and emulsions (e g , 25 to 50 days for ASA > 400 and up to 200 days for ASA < 80)
- Provide for entire replacement of high speed film (ASA $\geq$ 400) supply after an intense solar proton event

GAMMA AND NEUTRON ENVIRONMENT

- Plan experiment module deployment trajectory to minimize approach to and stay in high radiation areas around Space Base reactors
- Consider neutron and gamma sensitivity of experiments on detached modules when selecting deployment location and minimum approach to Space Base
- Restrict rendezvous separation distances from reactors when transporting unprocessed film
- Consider RNS approach and departure trajectories in selecting detached module deployment position to allow minimization and anticipation of experiment interference

ISOTOPE SOURCES AND DYNAMIC GENERATORS

- Provide for intact return to earth, of isotopes and contaminated waste, for disposal
- Consider locating laboratories using dynamic generators or isotopes in low traffic areas to minimize exposure of the crew

to maximize film life on board the Space Base, film must be stored in a shielded container. Storing a dosimeter along with the film would allow evaluation of the condition of a particular batch of film and enhance the flexibility of the experiment program between film resupply periods.

Similar consideration is indicated by the wide range of sensitivity to radiation exhibited by candidate Bioscience experiment specimens (Table 6-5). Those specimens particularly sensitive to radiation should be monitored by dosimetry to ascertain whether observed effects may be due to radiation.

Design for Reactor and Isotope Interference (Gamma and Neutron) - Certain portions of the experiment program - predominantly those associated with the astronomy discipline - are particularly sensitive to the radiation environment generated by the reactor power module or isotope sources. Those experiments whose measurements could be degraded by gamma or neutron radiation from sources on board the Space Base should be considered for detached module implementation. The source of these radiations are the reactor power modules of the Base and isotope capsules which may be associated with the experiment program. However, should back-up electrical power be provided by an isotope system (such as isotope-Brayton), experiment sensitivity and location could be significantly altered due to the gamma and neutron environment associated with these isotopes, e.g., Pu-238, Cm-244.

Design for Dynamic Generators - Dynamic generators (e.g., X-ray equipment) which may be associated with the experiment program must be designed to provide a minimum hazard to the Space Base program. Shielding and interlocks must be provided to protect crew members working with the equipment and also crew members in adjacent compartments and interfacing vehicles (should the equipment be pointed to the exterior of the Space Base vehicle). Once the design has been established, the configuration should be restricted from relocation and reorientation that could negate the safeguards that had been implemented.

In addition to crew protection considerations, the shielding and facility design should consider the possibility of other sensitive experiments which could be located in nearby compartments.

Design for Tracers and Isotope Sources - The extent of the protection equipment required associated with the use and storage of isotope tracers and capsules depends primarily on the quality of isotope/tracer to be used/stored in the vehicle (see Section 7.3.2). One of the prime considerations is the decontamination procedures which would have to be implemented in the event of release of isotope/tracer material in the Space Base. Storing of Isotope tracers in zero "g" portions of the Base may preclude contamination (spills) resulting from termination or loss of artificial "g" capability. While it would seem to be considerably easier to implement conventional decontamination techniques in an artificial "g" environment, an unexpected loss of this environment could easily result in a tracer spill. In any event decontamination techniques will have to be developed for zero "g" operations. A concept which could facilitate decontamination if a large release of isotope should occur involves the use of isolatable/removable modules. All isotope/tracer work and equipment could be located in this type of experiment module. In the event of isotope release, requiring extensive decontamination, the module could be returned to earth, by the Shuttle, for conventional decontamination.

Experiment Operations - The implementation of operational considerations associated with the experiment program can make a significant contribution towards the objectives of (1) minimizing data degradation and interference and (2) minimizing the radiation exposure to personnel.

Experiment planning indicates the necessity to shut-off experiments or ignore data collected from experiments sensitive to the South Atlantic anomaly environment. The sensitivity of film carried as part of the experiment program requires regular resupply and care must be exercised in deploying detached experiment modules containing film.

Experiment sensitivity to reactor radiation is crucial in planning detached module orbits in relation to the Space Base. Although parameters such as operating range, observation time, and communication power requirements are significant design considerations, the data from sensitive experiments can be negated if the minimum approach distance to the reactors is not controlled. A similar problem exists where the RNS radiation field is the source of the interference. Operationally, the dose from an arriving or departing RNS should be minimized with respect to the deployed experiment modules, as well as the Space Base.

Nuclear material associated with the experiment modules should be returned to earth for recovery. The use of the Shuttle for nuclear system transportation, recovery and disposal is discussed in Volume IV of this study.

The radiation exposure of crew members and the hazards that could be initiated by untrained personnel should be minimized by appropriate location of isotope and tracer sources in low traffic and specially designated areas.

6.3.1.5 Reactor Power Module Environment Effects During Special Operations

The direct radiation effects associated with operation of the reactor at the nominal power level of 330 kWt have been evaluated in the previous sections, in conjunction with the natural radiation environment. In addition to these predominant considerations, other reactor power module operating conditions and thermal characteristics may have an impact on the Space Base Program operations and equipments.

6.3.1.5.1 Alternate Reactor Conditions Effects

Two alternate reactor modes are of interest 1) the reactor shutdown after normal operation and 2) the reactor operated at the "emergency" power level.

Post Operation Shutdown. The radiation field from a shutdown reactor is due primarily to the accumulated fission product inventory and the activated NaK coolant. The radiation environment, in the habitable regions of the Space Base, produced by a shutdown reactor is significantly less than that produced when the reactor is operating. The shutdown reactor contribution is approximately 7×10^{-4} mrem/hr as opposed to 0.5 mrem/hr per reactor during operation. However, the shutdown reactor will presumably require servicing or replacement that may require operations near the lightly shielded end of the reactor. In this area the combination of the fission product inventory and activated coolant produce a substantial radiation environment. Figure 6-23 shows the environment in the vicinity of the shutdown reactor. This figure includes the dose contribution from the other operating reactor assuming operation at an emergency power level of 600 kWt.

However, the contribution of this operating reactor to the environment shown in Figure 6-23, is on the order of 10 mrem/hr. Therefore, the fission product and activated coolant dose from the shutdown reactor predominates early after shutdown. Dose rates early after shutdown range from 2 to 200 rem/hr in areas close to the shutdown reactor. Such an environment would pose a severe hazard to personnel attempting servicing operations even aboard a vehicle such as the Tug or Shuttle. Special procedures such as allowing fission products to decay, establishing approach corridors and providing special shielding would have to be implemented to minimize the hazard of overexposure to excessive gamma radiation. These procedures are discussed in Sections 7.3.3 and 7.3.4, Reactor Maintenance, Repair and Disposal.

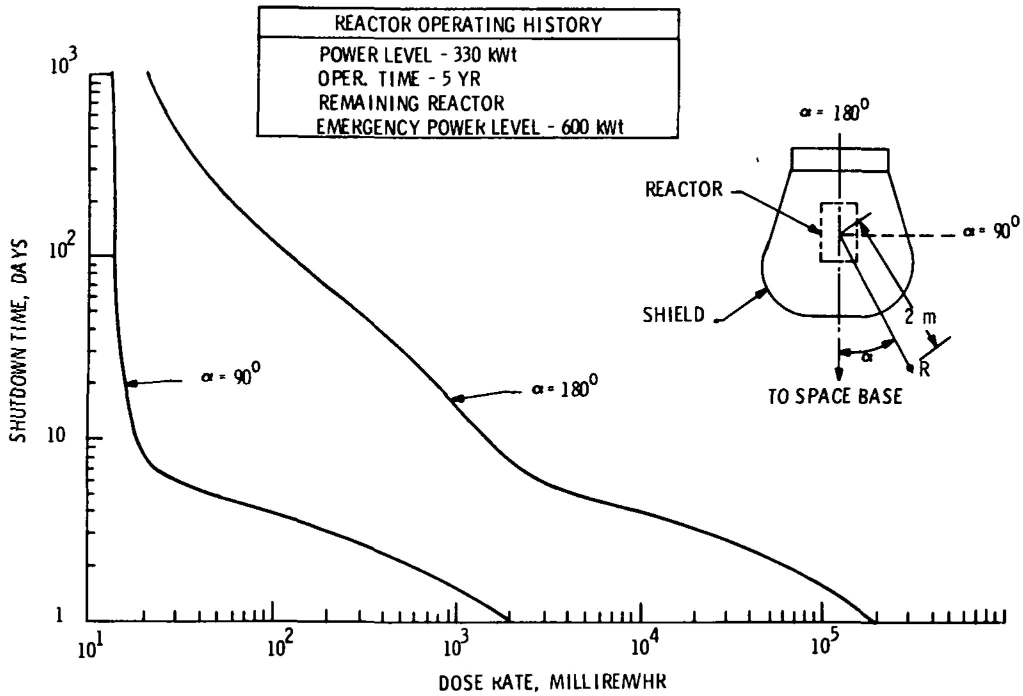


Figure 6-23. Radiation Dose Rate 2 Meters from Center of Shutdown Reactor as a Function of Time after Reactor Shutdown

Emergency Power Operation. The Space Base Electrical Power System may have the capability of increasing the normal reactor thermal power level in order to counteract the loss of electrical power that would occur during normal replacement or failure of one of the reactors. The thermal power level would be increased to approximately 600 kWt or nearly double the normal operating power level. As a result, the radiation environment on the Space Base will vary only slightly and the reactor contribution to the general radi-

ation environment around the vehicle will be essentially unchanged. Local radiation levels in the vicinity of the lightly shielded area of the reactor will vary somewhat from normal, however, these areas are restricted to normal traffic in any case. Therefore, the Space Base operations and environment would essentially be unaffected by the shift of reactor power to approximately double the normal thermal power level,provided this power mode is only implemented with one reactor shutdown.

6.3.1.5.2 Thermal Interference Effects

The Reactor Power Module rejects waste heat though radiators which, for the Brayton cycle conversion system, operate in the range of 350 to 500°K (165° to 440°F). This condition poses a potential hazard to EVA activities in the area of the radiators and also may interfere with terminal rendezvous operations.

Although nuclear radiation levels would allow restricted EVA in the area of the reactor radiators, contact with the hot radiator surfaces must be avoided during EVA in order to avoid suit degradation and subsequent depressurization. If high temperature radiators (>800°K) were to be employed, access around the radiator would be more restrictive due to the more intense IR radiations.)

Consideration has been given to using infra-red (IR) scanners and sensors as part of the attitude reference system of such vehicles as the Shuttle and detached (subsatellite) experiment modules. Since the reactor radiators present a significant source of IR radiation, they could provide spurious targets to IR horizon sensors and thereby disrupt attitude control during terminal rendezvous maneuvers. Horizon scanners which scan a wide field of view would likely intercept this false source of IR. Therefore, vehicles which rendezvous with the Space Base should be equipped with an attitude control reference which is insensitive to the radiator IR sources, or be restricted to a terminal approach trajectory which would preclude interference from the reactor radiators.

6.3.1.5.3 Design and Operational Considerations for Special Operations

Table 6-7 summarizes the guidelines for special Power Module operation environments.

Table 6-7. Reactor Power Module Special Environmental Conditions - Design and Operating Guidelines

DESIGN

- Consider special gamma shielding for Shuttle or Tug crew if immediate reactor servicing is required after shutdown
- Consider use of attitude control reference components in experiments and interfacing vehicles which are insensitive to radiator IR sources

OPERATIONS

- Allow reactor Power Module fission products to decay prior to performing operations near reactor docking interface
- Operation of a reactor Power Module at the emergency levels (600 kWt) should be restricted to an individual module to minimize the effects due to radiation
- Contact with thermally hot radiator surfaces must be avoided during crew EVA
- Consider restrictions in terminal approach trajectories of experiments and interfacing vehicles to preclude IR interference

6.3.1.6 Interfacing Vehicle Radiation Environment Effects

The Reusable Nuclear Shuttle (RNS), the Orbital Propellant Storage Depot (OPSD) and Detached Experiment Modules are interfacing vehicles associated with the Space Base Program, which may generate a nuclear radiation environment. The RNS would employ a NERVA-type rocket engine with its associated nuclear reactor. The OPSD may be provided with a nuclear reactor power system although the reactor and power conversion system are as yet undefined. Consideration has also been given to Detached Experiment Modules incorporating radioisotopes in the Electrical Power Systems.

6.3.1.6.1 Reusable Nuclear Shuttle Radiation Effects

The Reusable Nuclear Shuttle (RNS) poses a potential hazard to the Space Base under two operating conditions: thrusting and shutdown loiter. Since the baseline RNS operation orbit is 480 km at a 31.5 degree inclination (Reference 6-13), the interactions with the Space Base at a 55 degree inclination would depend upon respective launch times and orbital perturbations to produce encounters at the intersection of the orbit planes. The alternate nominal 30-degree inclination Space Base orbit would provide for more frequent orbital encounters. Therefore, the consideration of the RNS interactions with the Space Base was based on this latter premise.

RNS Thrusting. While the RNS is thrusting out of earth oribt, two potential sources of excessive radiation exist. The first is direct radiation from the RNS reactor. The intensity of this radiation is dependent on the distance from the RNS and the attitude of the RNS with respect to the line of sight to the Space Base. The latter consideration is due to the variation in shielding around the RNS. The second source of radiation is gaseous fission products which diffuse through the fuel matrix or particulate fission products resulting from corrosion of the fuel. (See Section 6.3.2.2.1.) The products may then be expelled in the rocket exhaust causing the exhaust plume to be radioactive (Reference 6-14).

Evaluation of the accumulated dose to a manned space vehicle, has been performed (Reference 6-2) for a "Leave Earth Maneuver" with the manned vehicle initially 1190 km (640 nm) ahead of or behind the RNS at start-up. The accumulated depth dose for these two positions was calculated to be 0.1 mrem and 2.3 mrem respectively. It is estimated that a startup as close as 19 km (10 nm) from the Space Base would result in an accumulated depth dose of at least 250 mrem. This implies that the RNS should be maintained at a position greater than 19 km (10 nm) from the Space Base at initial start-up in order to minimize crew dose and maintain depth does below the 200 mrem/day yearly average. With the implementation of suitable operating procedures, the RNS thrusting mode should pose a negligible hazard to the crew of the Space Base. These doses would also pose no threat of permanent damage to Space Base support subsystems. However, passage of the thrusting shuttle as close as 18,500 km (10,000 nm), line-of-sight, to sensitive experiment modules (e.g. FPE 5.5) would cause temporary experiment interference. Preliminary analysis (Reference 6-14) indicates that passage through the RNS expanded plume (contrail) should pose a negligible hazard to the Space Base, since a total dose per passage of less than 7 mrem is predicted. However, intermittent experiment interference for those experiments susceptible to gamma ray interference must be anticipated.

RNS Loiter. In order to fully utilize the capability of the RNS and Space Base/Station vehicles, it may be desirable to have the RNS loiter in the vicinity of a Space Base while accomplishing crew or material transfer. During such loiter maneuvers, the RNS will constitute a source of gamma radiation due to its fission product inventory. The strength

of the radiation source diminishes as a function of time after shutdown, as the fission products decay. Due to the characteristics of the RNS shielding provided for crew protection, the dose rate due to fission products varies as a function of view angle around the RNS. This variation is shown in Figure 6-24. Figure 6-25 shows the actual fission product dose rate at the 90 degree view angle position, 100 m(330 ft) from the RNS, as a function of time after shutdown. It can be seen that high dose rates can be encountered even after significant shutdown times unless advantage is taken of the RNS shielding. This can be accomplished by maintaining the RNS attitude such that it points toward the Space Base with the engine pointing away from the Base. Even in this attitude, gamma ray sensitive experiments on detached modules must be kept at sufficient distance to avoid interference with measurements. Separation distances on the order of 30 km (16 nm) would be required for those sensitive experiments which could not be kept forward of the shield. Similarly, logistic vehicles such as the Space Tug and the Shuttle should rendezvous with the RNS from the maximum shielded direction in order to avoid unnecessary exposure of crew and passengers.

6.3.1.6.2 Orbital Propellant Storage Depot Radiation Effects

Since the Orbital Propellant Storage Depot (OPSD) lacks definition as to its reactor power system and energy conversion mode, specifics of its impact on the Space Base Program under normal operating conditions are not possible at this time. However, assuming that the electrical power system would incorporate a reactor similar to the Space Base power system with moderate shielding, the OPSD would induce similar effects to those discussed in the previous sections. Since no direct contact is made between the Space Base and the OPSD the influence of direct radiation on the crew and subsystems would tend to be negligible if, for example, a separation distance on the order of 6 km is maintained. At this distance the maximum dose rate at the Space Base due to the OPSD would be about 0.01 mrem/hr, assuming a dose characteristic similar to that shown in Figure 3-12 of Section 3. This dose rate is 2 to 3 orders of magnitude less than the natural environment dose rate. The deployment of detached experiment modules must also be managed as discussed in Section 6.3.1.4 to avoid unacceptable experiment interference.

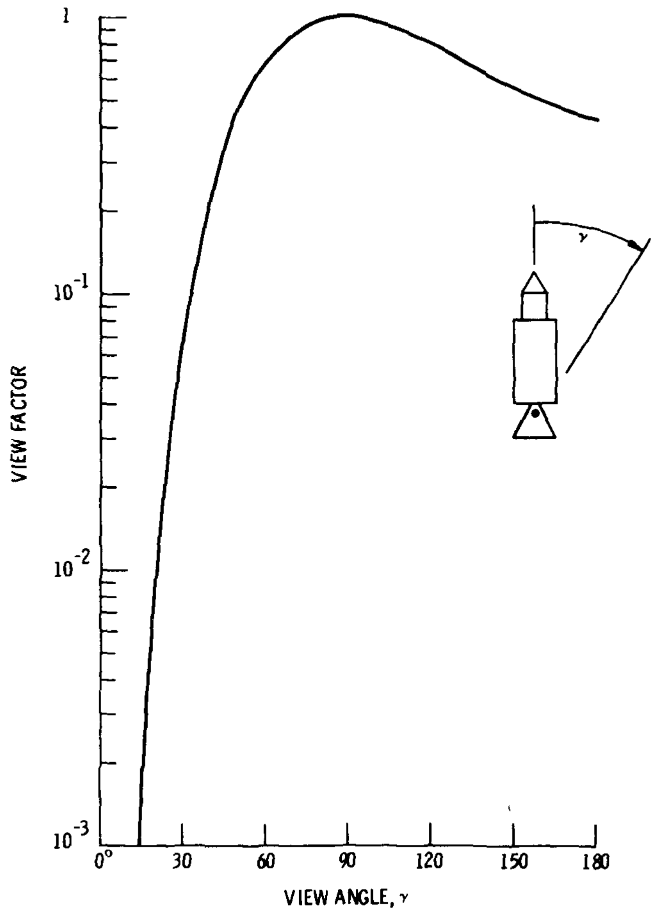


Figure 6-24. Effect of View Angle on Fission Product Gamma Dose Rate

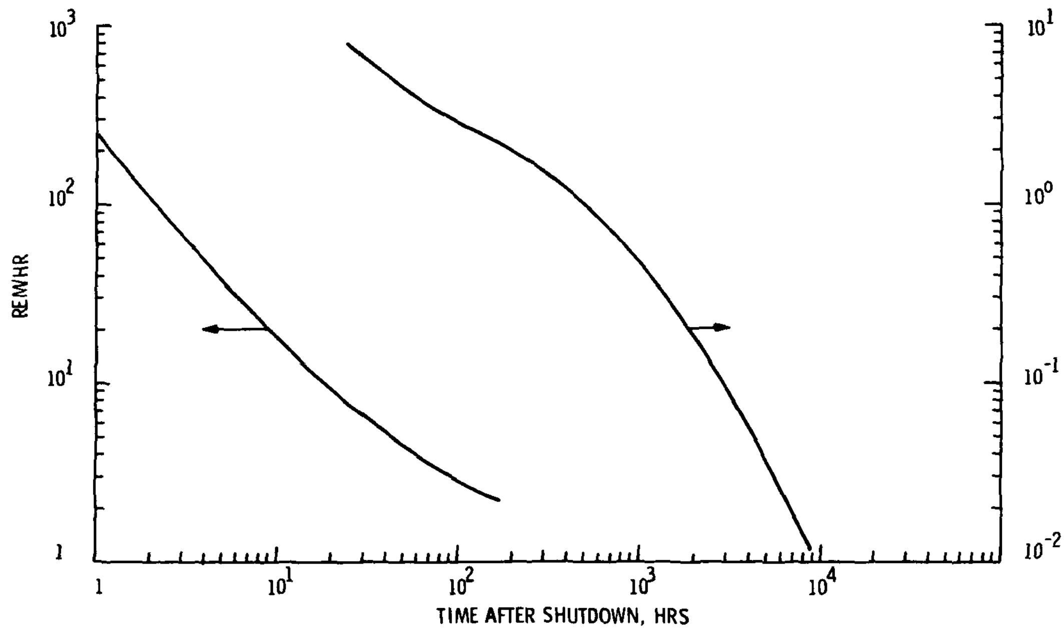


Figure 6-25. Fission Product Dose Rate from the RNS Versus Time After Shutdown for a 90 Degree View Angle and 100 m Separation Distance

While the OPSD cannot be neglected as a hazard source during normal operations, it would appear that the implementation of a combination of design and operational features (shielding,orbit selection and separation distance) would allow it to operate at a position easily accessible to the Space Base (e.g., through use of the Space Tug) while posing a negligible hazard to the Space Base.

6.3.1.6.3 Detached Experiment Modules Radiation Effects

As discussed in Section 3.8.4, consideration has been given to incorporating isotope heat sources with various energy conversion systems, as part of detached module electrical power systems. These sources would produce neutron and gamma radiation environments. As a result, dynamic interference could be induced in sensitive equipments on board the detached modules and also on board the Space Base when the modules are docked for refurbishment. In addition, when docked to the Space Base, consideration must be given to providing shielding for the crew engaged in servicing the modules as well as personnel and equipment in areas adjacent to the docking position.

The extent of the effects induced by modules which incorporate isotope systems depends to a large extent on the power levels required and the efficiency of the energy conversion system employed since these factors influence the total inventory of isotope fuel. Incorporation of shielding and limiting approach distance to radiation sensitive equipments can minimize the radiological effects of isotope powered experiment modules on the Space Base Program.

6.3.1.6.4 Design and Operational Considerations for Interfacing Vehicle Radiation Effects

As noted in Section 3.8.3, several of the interfacing vehicles may incorporate nuclear power sources. From a design and operational standpoint, it is important that the radiation field from these sources be recognized, e.g., during rendezvous and docking, and in the deployment of radiation sensitive equipment. Table 6-8 presents the design and operational guidelines associated with the normal operation of interfacing vehicles.

Table 6-8. Design and Operations Guidelines for Interfacing Vehicle Radiation Effects

DESIGN

- Consider auxiliary shielding of the crew engaged in servicing detached experiment modules containing nuclear sources
- Consider shielding of adjacent/radiation sensitive areas of the Base when detached experiment modules are docked for servicing

OPERATIONS

- Establish and maintain maximum shielded approach corridors to orbital vehicles employing nuclear power systems to minimize exposure of crew and experiment interference
- Establish minimum deployment range for vehicles utilizing nuclear power sources (eg , RNS start-up maintained at a position > 19km from Base)
- Intermittent experiment interference must be anticipated when thrusting RNS type vehicles are in vicinity of Base < 18,500km
- Restrict approach paths of vehicles employing IR (infrared) attitude control detectors to avoid interference from high temperature sources
- Establish minimum approach distances during RNS thrusting (arrival and departure) to minimize crew exposure
- Establish minimum rendezvous distances with shutdown RNS based on RNS attitude control failure modes

6.3.1.7 Experiment Laboratory Induced Radiation Effects

6.3.1.7.1 Dynamic Generator Radiation Effects

The effects of the dynamic generators may be characterized according to whether these generators produce ionizing or non-ionizing radiation. X-ray machines would be typical of those producing ionizing radiation whereas microwave generators (radar, microwave ovens, etc.) and lasers would be typical of those producing non-ionizing radiation.

The radiation effects due to x-ray exposure are similar to that characterized by gamma radiation as described in the previous sections for biological and subsystem damage and for experiment interference (see, for example, Figure 6-12, FPE 5.3). Since this equipment is not expected to be used continuously, its operation could be programmed to accommodate sensitive experiments. Therefore, the primary concern is to insure adequate procedures to prevent unauthorized operation and exposure and to provide adequate shielding to prevent radiation streaming to adjacent habitation and experiment areas. Such streaming to adjacent areas could cause spurious exposure of specimens and possibly biased or degraded data.

Biological effects induced by microwave generators are subject to considerable discussion (Reference 6-15). Evidence indicates that cataract formation may be induced. Whole body effects caused by heating when exposed to high power levels result in brain and other organ damage. However, some studies of radar workers who have been continuously exposed over several years indicate no detrimental effects (Reference 6-15). In terms of frequency, the range from 2000-3000 MHz represents the greatest hazard for cataract production. United States standards for microwave exposure is currently 10 mW/cm^2.

Laser equipment represents high intensity light and is a hazard to the eye. The threshold level for damage to the retina is 0.1 $joules/cm^2$. Precautions are necessary (procedures warnings, shielding, etc.) to prevent inadvertent exposures of the crew during operations where lasers are operating.

6.3.1.7.2 Open Isotope Sources Radiation Effects

Tracer elements have been identified as possible open isotope sources, i.e., usable without primary containment, e.g., injected into specimens. Because of the generally small quantities involved (microcurie inventories) there is no hazard from direct radiation. However, the use of these elements can lead to contamination of the Space Base or spurious experimental results due to lack of management of the products of their use. For example, excreta and tissue from biological specimens as well as contaminated trash must be segregated from the central waste management system to avoid undesirable tracer dosage to

other specimens and the crew in general, e.g. from recycled water. Also, gaseous by-products such as CO_2 generated as the result of using a Carbon-14 tracer must be prevented from release to the general Space Base environment if quantities involved would approach maximum permissible concentrations or interfere with experimental results (see Sections 6.3.2.3 and 7.3.2). The precautions against excessive release would preclude interference with End-of-Mission (EOM) operations. As a matter of environmental policy it is desirable to return tracer inventories to earth for disposal.

6.3.1.7.3 Closed Isotope Source Effects

Isotope capsules containing various inventories of isotope may be used as heaters for equipment thermal control, waste management system pyrolysis units, etc. The effect of these sources under normal operation is to locally increase the direct radiation environment. Evaluation of one current concept of a waste management system (Reference 6-5) identified in Section 6.3.1.1 indicates that properly shielded implementation of a 400 watt (thermal) Pu-238 capsule would not duly perturb the total local radiation environment on the Space Base. The effects of higher fuel loadings would have to be evaluated using the techniques described in Section 6.3.1. In addition to radiation, these sources can also represent a high temperature hazard for which protection must be provided.

6.3.1.7.4 Design and Operational Considerations for Induced Radiation Effects

Table 6-9 summarizes some of the key guidelines for the accommodation of induced radiation generators.

6.3.2 ACCIDENT CONDITIONS EVALUATION

The accident conditions and associated hazard sources have been previously identified in Table 6-2. The results of an evaluation of the hazardous effects of these conditions is presented in the following sections.

6.3.2.1 Reactor Power Module Accidents Radiation Effects

An identification of potentent power module accidents is contained in Section 7.2.1. The radiation effects of reactor power module accidents are discussed below.

Damage to the shield in orbit can occur through puncture by meteorites, or collision with space debris or vehicles. The damage may range from a small puncture to possible.

Table 6-9. Design and Operations Guidelines for Induced Radiation Effects

DESIGN

- Provide shielding to prevent radiation streaming from dynamic generators to adjacent habitation and experiment areas
- Provide capability to prevent inadvertent laser beam exposure of the crew (particularly eyes) during laser operations (e g , shielding, warning devices)
- Provide segregated waste management systems where isotope tracers are to be disposed of in biological waste and water
- Prevent release of tracer gaseous by-products (such as CO_2 from C-14 tracer) into the general Base environment
- Provide localized shielding of small isotope heat sources within Base modules
- Consider thermal protection where isotope heat sources are employed

OPERATIONS

- Prevent unauthorized operation of dynamic (induced) radiation generators
- Provide restrictive procedures (location, viewing, etc) during laser operation
- Provide for the return to earth of tracer and isotope inventories

complete removal of a large portion of the radiation shield. Collisions severe enough to penetrate the radiators and remove significant portions of the shield would be of such magnitude that the collisions would by themselves alert the Base of an emergency situation. Small penetrations by meteorites would be undetectable without some instrumentation and therefore could result in a continuous rise in radiation level at the Space Base.

Meteorite penetrations of the shield would likely be restricted to the outer LiH neutron shield. Considering the meteorite environment (Reference 6-16) and the reference shield configuration (Figure 3-10, Section 3. 8. 2. 1), it is extremely unlikely that meteoric particles would have sufficient energy to penetrate the radiator, LiH clad, LiH and the 9 to 15 cm of Tungsten gamma shield. Therefore, the results of a small shield puncture would be primarily a change in the neutron environment due to the damage to the LiH neutron shield. When LiH is exposed to vacuum at operating temperature, hydrogen dissociates from the Li (Reference 6-3) reducing the effectiveness of the neutron shielding. Based on this dissociation rate, Figure 6-26 shows the resulting increase in neutron dose and dose rate as a function of time after penetration. As can be seen from this figure, the hydrogen is

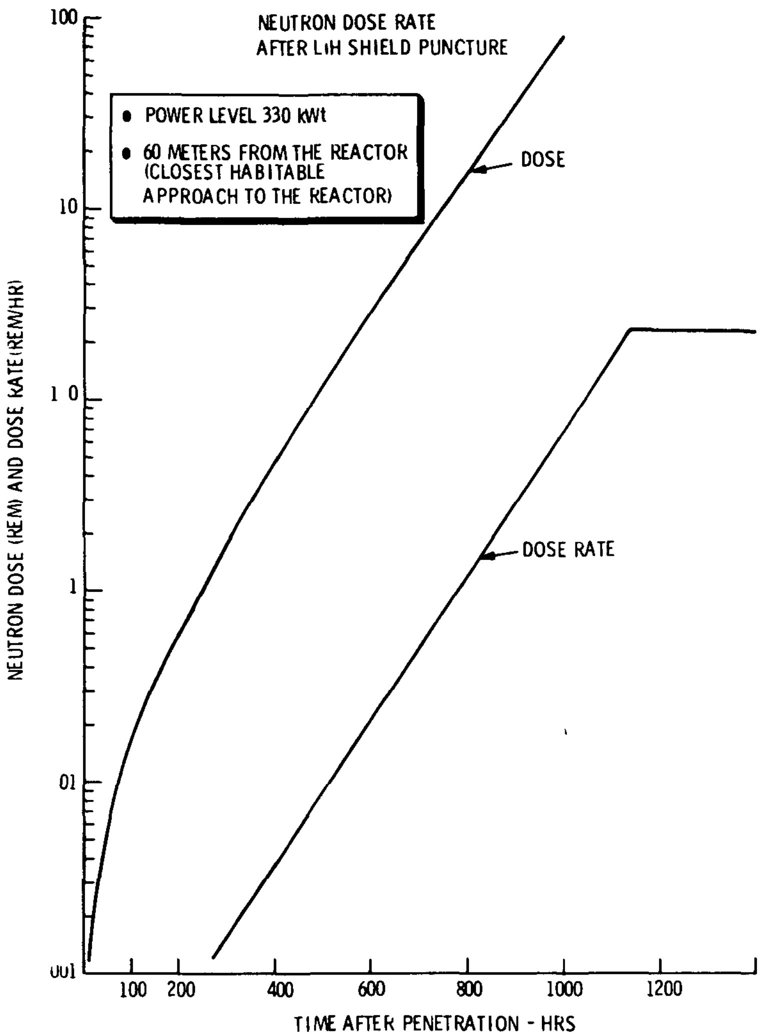


Figure 6-26. Accumulated Neutron Dose and Neutron Dose Rate after LiH Shield Puncture

essentially depleted approximately 1100 hours after the puncture occurs and the dose rate levels off to approximately 2 rem/hr. Figure 6-27 shows the total integrated dose at the Space Base (60 meters from the reactors) including the dose to the eye and the depth dose from the natural trapped radiation environment (Figure 3-7). The allowable 30-day dose levels are also indicated (see Section 4.2). These allowable levels are not exceeded providing a major solar flare does not occur during this period. The data of Figure 6-27 indicates that no immediate danger exists from a small LiH shield puncture. However, the situation must eventually be detected and corrected since unacceptably high dose levels would be accumulated ~ 900 hours after the penetration occurs. Since the reactor power module would have to be shut down and replaced in order to permanently resolve the hazard,

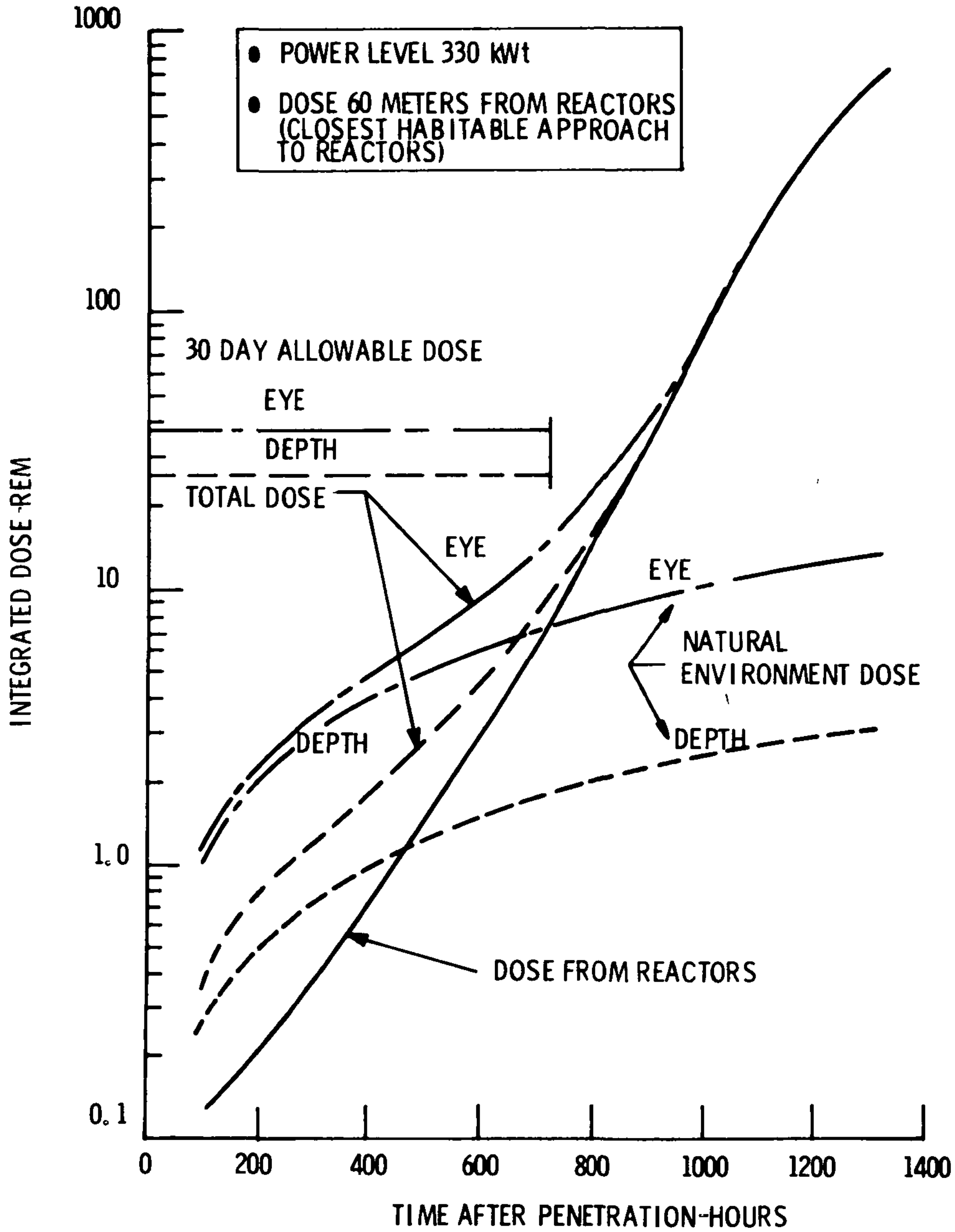


Figure 6-27. Total Integrated Dose After LiH Shield Puncture

even a small shield puncture would constitute a "safety marginal" hazard category. Since the LiH portion of the shield material would presumably be composed of multiple sealed compartments of LiH, early detection of a puncture could be determined by pressure sensors located in each compartment. In addition, a slow increase in neutron dose rate could be detected by the instrumentation associated with the On-board Radiological Safety Program (see Section 7.3.1).

Should a larger collision remove a portion of the external LiH shield, the total dose rate on-board the Base would be instantaneously increased by approximately 2.3 rem/hr. Such a dose rate is well above the daily allowable rate and would require prompt response, i.e. shutdown or jettison of the reactor, in order to minimize crew exposure. However, several hours would be available before portions of the crew would accumulate sufficient dose to eventually become incapacitated (see Appendix A, Section A.5). Although no immediate damage or injury to personnel would occur, the hazard should be categorized "safety critical" in order to minimize crew exposure.

A third possibility is a collision with a sufficiently large piece of debris or a space vehicle that would remove at least a portion of the entire shield (both neutron and gamma shielding), exposing the bare reactor. Under such conditions, the dose rate at the Space Base could be as high as 700 rem/hr. Such a dose rate is intolerable for periods longer than approximately four minutes. Longer periods of exposure would result in some members of the crew to exhibit partial incapacitation (vomiting), during the next 24 hours (see Appendix A, Section A-5). Therefore, the reactor power module must be immediately shut down and/or jettisoned. Shutdown with the reactor power module remaining at the power module mount would still result in a maximum dose rate of approximately 40 rem/hr from the fission product inventory and indicates that the reactor power module must not only be shut down within about 4 minutes, but jettisoned within about a half hour to avoid incapacitating the crew. Such an accident would represent a "Safety Critical" hazard.

Considering these last two damage conditions, an impact of the magnitude sufficient to destroy major portions of the reactor shield would also be likely to damage mechanisms which could effect shutdown of the reactor. Therefore, jettisoning and neutron poison injection (see Section 7.3.4) may be the only means of avoiding overexposure or safing the system under these circumstances.

It should be noted, however, that the probability of such a collision with orbital debris is relatively small. Analyses of collision probabilities based on the NORAD satellite catalog (Reference 6-17) indicates that the probability of the Space Base colliding with a piece of

orbital debris or orbital vehicle in a 10-year mission is approximately 1.18×10^{-2}. Since the reactors/shields provide a much smaller target, the probability of either reactor/shield being struck over a 10-year period is about 5×10^{-4}. The probability of the severe damage postulated above is even less since the damage depends on the relative velocity, the location of impact point, etc.

6.3.2.1.2 Activated NaK Coolant Release Effects

There are three sources of NaK (sodium potassium eutectic - 78 percent Potassium) in the Reactor/Brayton cycle power conversion system (see Figure 3-4) coolant loops:

- Reactor Primary Loop
- Intermediate Loop
- Waste Heat Rejection Loop

Alternative Brayton cycle systems which could be employed may utilize organic coolants in the Intermediate and Waste Heat Rejection Loops rather than NaK. In any case, due to the high neutron fluxes encountered in the reactor, the primary loop NaK coolant is activated. Radioactive decay of the activated NaK results in a gamma ray environment. The activation of the Intermediate and Waste Heat Rejection Loop coolant is negligible due to the low neutron fluxes encountered outside the reactor shield.

Release of NaK to the environment around the Space Base is of concern because of potential deposition of NaK on the spacecraft and the ensuing potential structural corrosion, equipment contamination and possible interference with EVA activity. In the case of activated NaK, the additional hazard due to radiation must be considered as well as those previously mentioned. Therefore, the release of activated NaK is considered here since it encompasses all the potential hazards.

Rate of release of activated NaK may range from a slow leak due to a meteorite puncture, to a spontaneous total release if a destructive reactor excursion were to occur (see Section 6.3.2.1.5). In order to obtain a quantitative "feel" for the radiation effects due to activated

NaK release, it was assumed that the total NaK primary loop inventory was dispersed uniformly and spherically and was deposited uniformly on Space Base modules that encountered the expansion. It was further assumed that the equilibrium activated NaK inventory at the 330 kWt reactor operating point is 700 curies.

Based on these assumptions, the initial dose rate at the artificial "g" modules would be approximately 32 mrem/hr. Since the effective decay constant of the NaK is approximately 1.28×10^{-5}/sec the total dose accumulated due to the NaK decay is approximately 0.7 rem. Based on these assumptions it appears that deposition of activated NaK on the habitable portions of the Space Base would not pose a severe radiation hazard to the crew. Experiments which are sensitive to gamma ray interference may exhibit degradation of data. However, the overall integrated dose and dose rate would be too low to result in permanent radiation damage to subsystems.

The non-nuclear hazards associated with interactions of the deposited NaK with the Space Base structure and equipments depends primarily on the temperature of the NaK when deposited and then the quantity deposited. Data (Reference 6-18) indicates that NaK exhibits long term compatibility with aluminum and aluminum alloys up to about 500°K (440°F). Therefore, there is the possibility that no excessive corrosion of the Space Base structure would occur. However, the eventual surface temperature may be determined by the potential degradation of thermal control coatings which could then cause a rise in temperature above the compatibility levels. The concept of strippable thermal coatings (Ref 6-19 and 6-20) for long-term thermal control system maintenance might provide a solution to this condition.

An additional consideration is the effect on personnel engaged in EVA. Again, the hazards here are (1) direct radiation depending upon the quantity released and the release mechanism (spontaneous or slow) as well as (2) compatibility with the space suit. Space Base operations would preclude EVA when a NaK coolant release is suspected (reduction in coolant loop pressure or flow rate). Consideration should be given to providing an EVA suit which would be compatible with NaK in order to allow emergency EVA activity to be accomplished safely in the event of NaK release.

The effect of NaK released to the Space Base environment depends primarily on the quantity and temperature of the NaK released and the quantity deposited in a given location. As a result, the hazard category may vary from safety negligible (release of minute quantities) to safety critical (large release, large quantity at high temperature deposited in localized area, with subsequent structural corrosion).

6.3.2.1.3 Fission Products in NaK Coolant Release Radiation Effects

The previous section discussed the radiobiological hazards involved with the release of activated NaK and related NaK hazards. An additional consideration is the release of activated NaK which contains fission products. This fission product release may be brought about by various combinations of events (see Appendix C) but requires that the reactor fuel element cladding is breached in some manner. The mechanisms for release of the contaminated NaK would of course be the same as described in the previous section. The difference in the total effect would be the additional radiation field caused by the fission products entrained in the released NaK.

The severity of the effect of the release of fission products will depend on the quantity actually released. The actual quantity released under a given failure would vary with the number of fuel elements affected, the quantity of fission products released to the NaK in the primary loop, the length of time the breached fuel element condition persisted and the magnitude of the NaK release. For a gross release, such as the destructive excursion discussed in Section 6.3.2.1.5, data exists which allows some approximation of the fraction of the fission product inventory released (Reference 6-21) and therefore an estimate as to the extent of the effects involved. However, no comparable data is readily available that would allow a quantitative evaluation of the effects resulting from slow leakage of fission products into the NaK and their subsequent release. Therefore, for the purposes of this evaluation, only a qualitative assessment of the effects of released fission products in the coolant was attempted.

From the standpoint of exposure to direct radiation and experiment dynamic interference, the fission products are predominantly a source of gamma-rays. Consequently, the Space

Base structure will be relatively ineffective in shielding these gamma rays as compared to electrons (Beta radiation). The hazardous condition would have to be detected (see Section 7.3.1) and corrective action taken in order to protect the crew. Such action would also preclude exposure of subsystems to a permanently damaging dose. However, equipment and experiments sensitive to gamma radiation are likely to exhibit interference.

From the previous discussion, it is apparent that a considerable range of effects could be experienced. Depending on the severity of damage, i.e., the quantity of fission products released, the hazard category could range from "safety negligible" to "safety critical" as in the case of the activated NaK without the fission products.

6.3.2.1.4 Non-Destructive Reactor Excursion Radiation Effects

A reactor excursion is the unplanned operation of the reactor above its normal operating point resulting in higher thermal power and higher radiation fluxes. A non-destructive excursion would result from controlling the excursion, i.e. partial or complete shutdown of the reactor, either through safeguards (see Section 7) or due to the inherent characteristics of the reference ZrH reactor (see Section 3.2.2.1) so that the reactor remains mechanically intact. Assuming that these conditions are fulfilled the sole result of the event is a momentarily increased radiation level in the vicinity of the Space Base. Since the reactor is assumed to remain structurally intact, these radiation levels would be attenuated by the reactor shield.

In estimating the magnitude of a possible excursion, the rationale described in Volume III, Part 2, Section 4.1 and data from References 6-21 and 6-22 were used. It was assumed that the "worst case" non-destructive excursion could be nearly the same magnitude as that assumed for the maximum credible destructive excursion, i.e. 100 MW-sec.

Based on these assumptions, the total dose due to the excursion would be on the order of 0.04 mrem, which is negligible. The maximum dose rate to subsystems and experiments would be on the order of 100 rad/hr. As pointed out in Section 4, the only subsystem equipment likely to be dose rate sensitive are equipments such as star trackers. However, the

effect is simply degraded data (noise) which would be of negligible consequence since the duration would be 1 millisecond or less. The same would be true in the case of radiation sensitive experiments.

Since the reactor power module may be shut down after such an event with corresponding reduction in electrical power availability the category of the hazard would be at most "safety marginal." In the event that the Space Base Electrical Power System possessed an emergency power mode, such as discussed in Section 3.2.2.1, the hazard category would be "safety negligible," since full functional capability would be retained.

6.3.2.1.5 Destructive Reactor Excursion Radiation Effects

This section represents a preliminary assessment of the effects of a destructive reactor excursion, in orbit. (Section 5.1.1.2 discusses effects during the prelaunch phase and Section 6.2 of Volume III Part 3 of this study discusses the terrestrial nuclear safety aspects of the event.) The destructive excursion is considered to be an event similar to that described in the previous section with the exception that the magnitude and/or duration of the energy release is sufficient to cause mechanical/structural disassembly of the reactor. Design features associated with the reference ZrH Reactor greatly reduce the likelihood of a destructive reactor excursion. However, characteristics and failure modes of as yet undefined auxiliary systems (such as the on-board reactor control system) and unplanned, but possible, events (such as collisions) may occur, which could lead to a destructive excursion. Therefore, the emphasis in determining the effects of the postulated events has been placed on estimating the magnitude of the hazards and the time period available for instituting corrective procedures following a destructive excursion.

In estimating the effects of a destructive excursion, the following sources of radiation were postulated:

1. Increased radiation due to operating power level during the excursion.
2. An expanding fission product cloud (particulate and gases) and activated NaK cloud around the Space Base following disassembly of the reactor.

3. *Deposited fission products and activated* NaK *on the portions of the Space* Base passing through the cloud.

4. Reactor debris remaining in the vicinity of the Space Base.

From the standpoint of the response time available, the initial pulse of radiation during the excursion along with the expanding fission product and NaK cloud are important since they take place over a very short period of time. The deposited fission products, NaK and the resulting reactor debris will affect the long term radiation environment around the Space Base.

Excursion Prompt Radiation Effects. As seen in the previous section, the radiation dose and dose rates during a non-destructive reactor excursion cause little effect on the Space Base, providing the reactor shield remains intact. However, in the case of a destructive excursion, the actual position of the shield during the first few milliseconds of the excursion and of break-up of the reactor is extremely important in determining the radiation dose experienced at the Space Base. Should the shield be removed or cracks occur during the actual power pulse, the prompt dose rate at the extremes of the habitable area of the Base could range from 40 rem to 120 rem (see Volume III, Part 2, Section 4.4.2). Since one of the mechanisms for terminating the excursion is the actual break-up and distortion of the critical assembly, it is conceivable that at least cracks could occur in the shield assembly. However, due to the massive nature of the shield,it is questionable whether large portions of the shield could be removed during the time period over which the actual excursion takes place. Therefore, it is possible that some areas of the Space Base could be exposed to very high radiation doses but doubtful that the entire crew would receive these doses during the excursion. A percentage of those personnel nearest the reactors, who are exposed to the high dose levels (120 rem) would experience some incapacitation (vomiting) during the first ten hours after exposure (see Appendix A and Section 4.1.2).

Fission Product and NaK Cloud Radiation Effects. To estimate the effect of the initial release of the fission products and NaK it was assumed that fission product particulate

and gases along with the entire activated NaK inventory in the primary loop was isotropically released at the end of the power excursion. The fraction of the fission product inventory released as fines and particulate was assumed to be approximately 20 percent based on the SNAPTRAN-2 destructive test results (Reference 6-23). The primary source of radiation from the expanding cloud is the gamma radiation component from the fission products. The activiated NaK component is initially much smaller and is only considered from the standpoint of deposition on the modules.

The fission product radiation may be divided into two components: those created during the excursion, and the inventory due to the normal power operation of the reactor (Vol III Part 2 Section 4.2.2). The cloud composed of these two components was assumed to expand in a spherical, isotropic manner according to the analysis shown in Reference 6-24.

The resulting dose from the passing cloud is shown in Figure 6-28. The total integrated dose from the expanding cloud is approximately 6 rem. As shall be seen, this dose is small compared to other dose sources that follow a destructive excursion. However, since the bulk of the expansion is over in a matter of seconds, interference with equipments due to the high dose rates of gamma radiation (3×10^4 rad/hr) would be likely.

Deposited Fission Products and NaK Radiation Effects. In Sections 6.3.2.1.2 and 6.3.2.1.3 the effects of released NaK and fission products were discussed. Based on the results of the SNAPTRAN-2 tests (Reference 6-23) and the model for the gaseous and particulate cloud expansion (Reference 6-24) the time-line effects of deposited Nak and fission products may be assessed.

It was assumed that the NaK and fission products, expanding in the manner described in the previous section were deposited uniformly on Space Base projections encountered during the expansion. From the baseline configuration, the artificial "g" modules represent the largest projected area to the expansion and therefore radiation doses were based on a position at the center of these modules. Figure 6-28 shows the accumulated dose as a function

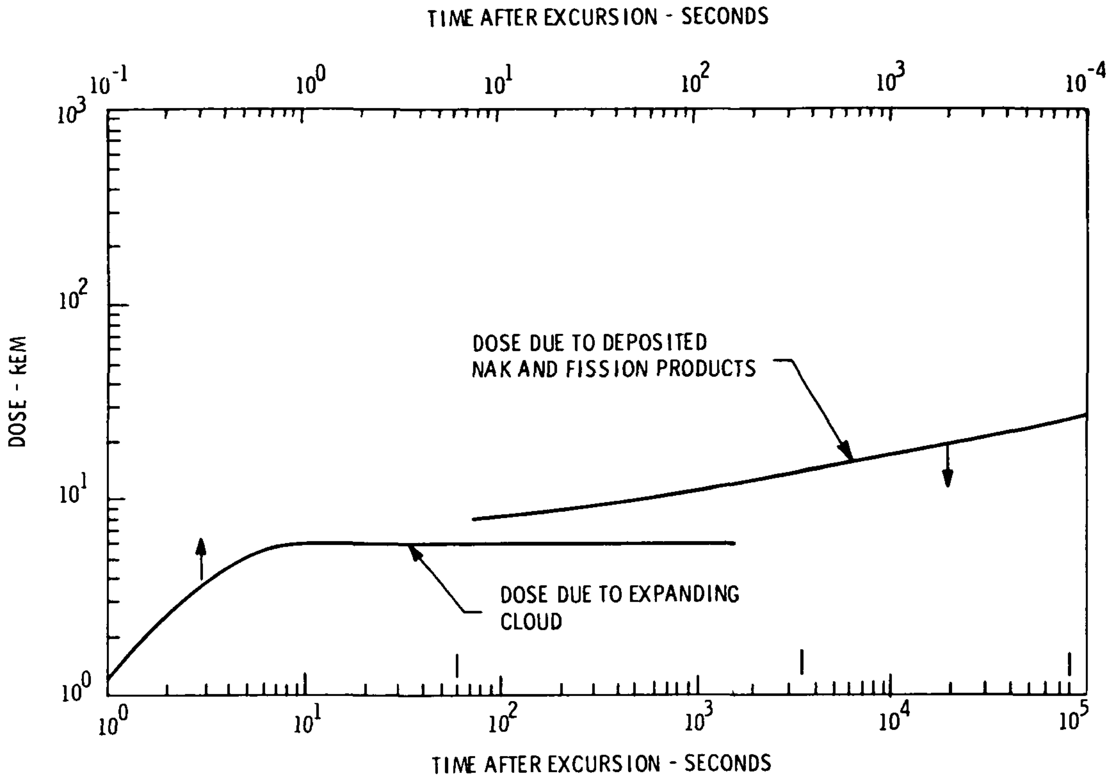


Figure 6-28. Dose Due to Dispersing Fission Products and NaK

function of time due to deposited fission products and NaK. As can be seen, the total dose due to this source of radiation is approximately 26 rem one day after the excursion.

Radiation Effects from a Destructive Excursion and Associated Debris. The previous sections have dealt with only 20 percent of the total fission product inventory of the reactor. The remaining 80 percent is composed of "debris", that gaseous material (which has not been released from the fuel) and the remaining solids, in the form of intact fuel elements or "chunks" of fuel elements. The determination of the distribution of this debris is beyond the scope of this study. It is conceivable that the distribution could range from a widespread dispersion in the vicinity of the Space Base, to the configuration where the bulk of the debris remains at, or in the reactor power module due to the configuration of the structure. This latter case was assumed in order to establish a quantitative "feel" for the severity of the radiation from the reactor debris. In addition, it was assumed that one fuel element was lodged at a position at the mid-point of the zero "g" axis of the Base.

Based on these assumptions Figure 6-29 shows the time-line total dose, at the extremities of the zero "g" axis from all radiation sources caused by the destructive excursion. Under these conditions personnel in the habitable sections of the Space Base, closest to the reactor, would receive an LD-10 dose (dose required to kill 10% of those exposed) within 1 minute after the excursion occurred. If the conditions postulated persisted, personnel in this area would receive an LD-90 dose in about three hours. It should be noted that Figure 6-29 does not include the dose that would be received from radiation during the excursion, if the shield were damaged, so that at least locally more severe conditions could exist.

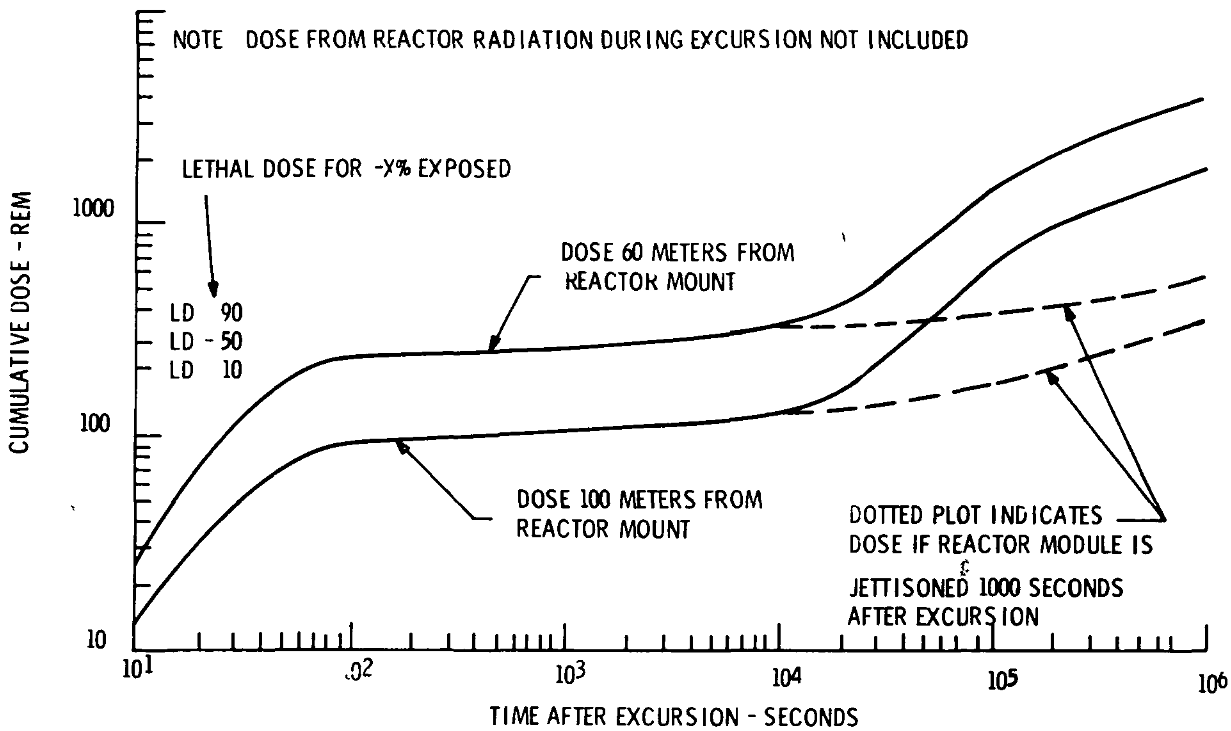


Figure 6-29. Total Radiation Dose Timeline at Space Base Extremities Due to a Destructive Reactor Excursion

Summary. The effects described in the preceding sections are highly dependent on the distribution of the reactor debris after the excursions. The consequence of this dependence can be illustrated by the different approaches to saving the crew that would have to be implemented. If the debris were to remain primarily at the reactor mount, then promptly jettisoning the power module (see Figure 6-29) would minimize the crew's exposure and facilitate subsequent space rescue operations. If the majority of the debris were to be

dispersed randomly about the Space Base, jettisoning the power module would have little effect and the Space Base orbit would have to be promptly adjusted to leave the orbit of the debris. In either case, it is likely that some of the crew would receive a lethal radiation dose, and that the Base would be sufficiently contaminated that it would have to be abandoned. These consequences indicate that a destructive reactor excursion must be categorized as "safety catastrophic."

In addition to the effects on the Space Base, the orbiting debris may eventually cause experiment interference in the detached experiment modules, and complicate their retrieval by the Shuttle.

6.3.2.2 Interfacing Vehicle Accident Radiation Effects

6.3.2.2.1 Reusable Nuclear Shuttle Accident Radiation Effects

Three RNS accident conditions have been identified which could result in a potential hazard to the Space Base Program. Two of these conditions, i.e., the fission product contamination of the rocket plume and the destruction of the reactor, have been analyzed in Reference 6-14. The third, loss of attitude control is important during RNS maneuvers close to the Space Base, and would generally apply only when the RNS and Space Base are in rendezvous compatible orbits.

Fission Product Ejection Radiation Effects. Fission products can be ejected from the RNS engine either in the form of gaseous products diffusing through the fuel matrix, into a coolant channel or as free fuel beads resulting from corrosion of the fuel. Analysis of the resulting distribution in the rocket plume and the encounter of the Space Base with the fully expanded contrail is discussed in Reference 6-14. The results of these analyses indicate that a dose of about 7 mrem would be accumulated on board the Space Base during passage through the contrail. This dose would have a negligible effect on crew safety.

Considering dose rate induced effects, the total passage time through the expanded contrail is about 450 sec., resulting in an average dose rate of about 56 mrem/hr. As a

result, the photon flux would be on the order of 10^4 to 10^5 photon/cm^2-sec. This flux would be sufficient to disrupt sensitive experiments (such as FPE 5.1) as they pass through the contrail. Therefore, such experiments would have to be turned off or data ignored during encounters with the thrusting RNS, if RNS plume contamination is detected. This will not be a continuously recurring problem, since particulate fission products ejected from the reactor plume are not expected to remain for long at orbit altitudes of about 500 km (270 nm). This is due to the fact that the relative earth velocity of the ejecta would be 300 to 900 m/sec (1000 to 3000 ft/sec) much less than the characteristic orbital velocity of approximately 7500 m/sec (Reference 6-14).

Destructive Disassembly Radiation Effects. A large portion of the fission product inventory would be released in a loss of coolant accident, followed by destructive disassembly of the RNS engine and reactor. The departure of the RNS is initiated from a position behind the Space Base (relative to the orbital velocity) and at a separation distance, at startup, of at least 30 km (16 nm) (Reference 6-2). It is unlikely that an excursion of sufficient energy release could occur that would produce a catastrophic (lethal or debilitating) prompt radiation dose to the Space Base over a 30 km (16 nm) separation distance. However, no data exists which allows quantitative evaluation of this potential hazard. Analyses performed in Reference 6-14 indicate that following the loss of coolant accident, the dose from fission products to an astronaut on board the RNS would be on the order of 20 to 40 rem. The separation distance from the Space Base should reduce the dose to Base personnel to a level well below catastrophic conditions. The debris released could cause experiment interference over long periods of time (several months) since the orbital residence time of the debris is expected to be relatively long.

Loss of Attitude Control Radiation Effects. To maximize the utility of the RNS, it should be capable of making approaches to the Space Base for the efficient transfer of cargo and personnel. As pointed out in Section 6.3.1.3.1, this can be accomplished by maintaining RNS attitude such that the Space Base is protected by the RNS shield. In the event of loss of attitude control, the Base could be exposed to relatively high gamma radiation from the RNS fission product inventory. As can be seen from Figure 6-25 dose rates could be as

high as 250 rem/hr at a point 100m (330 ft) from the RNS. If loss of control persisted for even a few minutes, Space Base operation (crew rotation schedule, gamma ray sensitive experiments, etc.) would be disrupted. However, with a suitable selection of approach distances and RNS attitude control system implementation, the hazards associated with the occurrence of this accident in the vicinity of the Space Base can be minimized.

6.3.2.2.2 Orbital Propellant Storage Depot Accident Radiation Effects

It has been assumed that the OPSD will have an electrical power system with a reactor similar to that employed on the Space Base. Therefore, the hazardous conditions associated with this reactor will be similar to those discussed in Section 6.3.2.1. The initial effects of these conditions on the Space Base will be less severe because of the separation distance maintained between the two vehicles. However, dispersed radioactive debris would interfere with experimentation and space operations in orbits which are close to the OPSD orbit.

6.3.2.3 Experiment Laboratory Accident Radiation Effects

6.3.2.3.1 Dynamic Generator Accident Radiation Effects

The accidents associated with dynamic generators result primarily from inadvertent turn-on while personnel are in an exposed area, or the intrusion of unauthorized personnel into a restricted area (either intravehicular or extravehicular) while equipment is being operated. The possible effects of exposure have already been discussed in Section 6.3.1.4 and would be the same under accident conditions. The nature of the possible radiological accidents is such that control and minimization of the hazards can be accomplished by appropriate administrative control, provided that design precautions for exposure control under normal operation have been implemented (see Section 6.3.1.4.1). These administrative controls would include warning signs, signals indicating equipment operation, equipment access restrictions and restriction of general operations, if necessary, during equipment operation.

6.3.2.3.2 Open Isotope Source Accident Radiation Effects

The primary accidental hazard source condition associated with the use of open isotope sources is release of the isotope to the Space Base environment. This hazard differs from the radiation hazards previously discussed in that internal rather than external radiation exposure is considered. The consequences of the resulting hazard depends on the isotope, the quantity released, the form of the isotope (solid, liquid gas, particulate) and the location in the vehicle. (See Section 7.3.2.)

Knowing the isotope involved is important in establishing the critical organ effected, e.g. bone, lung, thyroid gland, etc. The quantity released is of major importance since it determines the degree of possible exposure. The form of the isotope (gas, particulate, solution) relates to the severity of the hazard in the degree of dispersion that is to be expected and also, to some extent, the susceptible organs. Appendix A, Section A-5 discusses internal exposure and maximum permissible concentrations (MPC) for a variety of radionuclides. (Vol IV Part 2 App.D also discusses some aspects of the risk of exposure to various isotopes.) In terms of space application, the location of the isotope release in a Space Base is important for dispersion and decontamination considerations. For example, a release of liquid material in the artificial "g" section would more easily be isolated and retrieved than in the zero "g" section of the vehicle.

Although present estimates of the quantity of isotopes tracers that would be carried on a Space Base would be in micro-curie quantities, the MPC for continuous exposure could be exceeded if large inventories of tracers were released. Since a wide variety of tracer elements are expected to be used, the most important factor influencing the severity of the effects would be the quantity stored on-board, and as a result the hazards could range from safety negligible to safety catastrophic. Equipment requirements and general handling procedures for use with isotopes are discussed in Section 7.3.2.

6.3.2.3.3 Closed Isotope Source Accident Radiation Effects

Two accident source conditions associated with closed isotope sources (isotope capsules) are 1) failure or removal of biological shielding which may be associated with the source,

and 2) failure of the isotope encapsulation. The first of these would cause effects similar to those described in previous sections for direct exposure to radiation. In addition, the type of radiation (particles) would be similar to that of the reactor and natural radiation environments since the most likely isotopes to be used would be Pu-238, Cm-244, Sr-90, Co-60, etc. (See Reference 6-25.) Therefore, biological effects and subsystem and experiment damage would be similar and assessment of effects would vary according to the particles emitted by the particular isotope and the quantity of isotope used on board.

Failure of the isotope encapsulation material results in the internal biological exposure discussed in the previous section. This failure could range from failure of vents associated with the release of decay product gases (e.g., in the case of Pu-238, the alpha emitter-Radon) to release of isotope particulate matter. As in the case of the isotope tracers the severity of the hazard would depend on the severity of the breach and the quantity of isotope or radioactive gases released.

The design and operational considerations which are recommended to eliminate the hazards or reduce the effects of the hazards just described are presented in Section 6.3.2.4.

6.3.2.4 <u>Design and Operational Considerations for Accident Radiation Effects</u>

Many of the guidelines presented in the previous sections dealing with radiation effects during normal operations apply under accident situations. Table 6-10 summarizes the key guidelines for implementation for the accident situations discussed.

Table 6-10. Design and Operations Guidelines for Accident Conditions

DESIGN

- Provide instrumentation to detect reactor shield punctures/damage
- Provide radiological instrumentation to detect increased radiation resulting from shield damage
- Consider use of reactor core neutron poison injection to provide reactor safing
- Design for "no reactor excursion" capability
- Consider use of NaK compatible EVA crew space suits
- Consider use of strippable coatings on exterior surfaces of Base for ease of decontamination
- Provide NaK leak detection capability
- Consider a rapid response PM jettison capability
- Consider prompt rescue capability of the entire Space Base crew
- Consider providing sufficient orbit adjust capability to rapidly change Space Base orbit altitude

OPERATIONS

- Restrict and control interfacing vehicle approach distances and attitudes
- Avoid EVA when NaK leaks are suspected
- Perform crew rescue when radiation levels in or around Base are intolerable

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SECTION 7

SPECIAL STUDIES

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SECTION 7
SPECIAL STUDIES

7.1 GENERAL

Several special design and operational studies were performed of a Space Base mission to provide additional nuclear systems safety considerations for use in future manned space programs.

7.2 NUCLEAR SAFETY DESIGN STUDIES

The reactor power modules are the largest single source of radiation from Space Base program hardware. Therefore, emphasis has been placed on the hazards presented by reactor power modules and the design features important to nuclear system safety.

These studies address nuclear system safety aspects related to:

1. Accidents to Power Module which may cause a nuclear hazard
2. Reference Reactor Power Module Design Considerations
3. Power Module/Space Base Configuration
4. The Use of Alternate Power Conversion Systems
5. The Use of Alternate Reactors, and
6. Power Conversion System Configuration

The results of these studies are intended to provide the designer with guidelines to assess the relative impact on nuclear safety of reactor power module design features. Some options which offer attractive nuclear safety advantages may adversely affect the system design, performance, operations and cost. These considerations must be evaluated prior to actual program implementation.

7.2.1 IDENTIFICATION OF ACCIDENTS TO POWER MODULE WHICH MAY CAUSE A NUCLEAR HAZARD

This report summarizes accidents occurring in or to the power module exclusive of the reactor, which could conceivably result in a nuclear hazard. The accident sequence is examined from the time it originates in, or impacts upon, the power module until the appearance of the nuclear hazard. No attempt is made to identify all the accidents external to the power module which may cause a failure. As an example, numerous explosive events in or near the Space Base could sever one of the coolant circuits in the power module. In this study, the rupture of the cooling line is considered to be the accident rather than the original explosion.

The basic definition of the power module was that described in Section 3 with additional subsystems and components assumed to complete the system. Table 7-1 lists the subsystems and components comprising the power system with the added components designated with asterisks.

7.2.1.1 General

Two general types of single-failure accidents in the power module would present a nuclear hazard to the Space Base. They are:

1. A failure or rupture of the reactor coolant containment
2. A fracture or cleavage in the shield assembly.

The former accident would release activated NaK and, perhaps, fission products to the Space Base vicinity or into the intermediate heat transfer loop, a portion of which is located outside the shield. The latter accident would result in a high nuclear radiation field in the direction of the shield breach.

In all accidents except the two identified in the previous paragraph, multiple failures would be necessary to create a nuclear hazard. The potential hazards can be prevented IF;

Table 7-1. Composition of Power Module Components

Reactor Loop	
• Reactor	• Accumulator**
• TEM pumps (2)*	• Fill lines and valves**
• Piping	• NaK - NaK heat exchanger
Intermediate Loop	
• TEM pumps (2)*	• Fill lines and valves**
• Piping	• NaK-gas heat exchangers (3)
• Accumulator**	• Isolation valves @ HX inlet (3)
Power Conversion Loop (3)	
• Turbine-alternator-compressor (TAC) unit	• Gas - NaK waste heat exchanger
• Recuperator	• Turbine bypass valve and/or cutoff valve**
• Ducting	• Gas management system
Primary Heat Rejection Loop (3)	
• Primary radiator (3) coolant circuits sharing fin surface)	• Accumulator**
• Motor-pump assembly (2)	• Fill lines and valving**
• Piping	• Insulating shroud
Secondary Heat Rejection Loop** (3)	
• Secondary radiator (3 coolant circuits sharing fin surface)	• Piping
• Pumps	• Accumulator
	• Fill lines and valving
Aftercooling Loop**	
• Heat exchanger	• Piping
• Pump	• Accumulator
• Radiator	
Control Systems	
• Engine controls**	• Electrical system control
Shield	
• Lithium hydride neuton shield	
• Heavy metal gamma shield	
• Cooling system**	
• Pump	
• Piping	
• Radiator	

*More recent concepts employ Electromagnetic (EM) Pumps
**Assumed to exist in system

1. The accident or its effects can be detected early

2. The reactor can be shutdown

3. The reactor afterheat can be rejected from the power module.

7.2.1.2 Discussion of Results

The failure or accidental damage to each of the power module components was examined as a function of the following mission or power module operating phases; normal operation, power module startup, power module shutdown, prelaunch, launch, and power module disposal. For each identified failure, a succession of possible events and probable corrective or emergency actions was defined. The immediate and subsequent effects of the failure on power module operations was determined along with the possibility of an immediate nuclear hazard. A sequence of corrective and emergency actions was designated which would allow continued operation of the power module, if possible, and would shutdown the system if corrective action failed or was impossible. The next step evaluated the consequences to the power module if all emergency corrective actions failed and identified the resultant potential nuclear hazard.

Table 7-2 summarizes the results of the failure identification for the normal orbital operation phase of the power system. In most cases the information is straight forward but some explanatory comments follow.

It has been assumed in this study that some type of reactor aftercooling subsystem will exist on a Space Base. The existence of aftercooling capability is moot since the study must consider the consequence of its failure even if it does exist.

The rupture of the reactor cooling loop is identified as an immediate nuclear hazard because of the release of activated coolant. If the reactor cavity and the gallery can be confined, vapor-tight, then the danger of an immediate nuclear hazard is greatly diminished.

Table 7-2 Power Module Accidents Which May Result in a Nuclear Hazard

ORBITAL MISSION PHASE

Accident	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potential Nuclear Hazards
• Failure of reactor loop TEM pump					
- Thermoelectric circuit failure	Cessation of reactor cooling flow	None	Activate redundant pump, SR&AA*	Overtemperature/meltdown of reactor components	Release of fission products and/or activated coolant
- Loss of pump cooling					
- Rupture of coolant channel containment	Loss of coolant from reactor loop	Release of activated coolant	SR&AA		
• Failure or puncture of reactor loop piping accumulator fill lines etc					
• Failure of reactor loop heat exchanger					
- Rupture of reactor side					
- Leakage from reactor side to intermediate side	Introduction of activated coolant into intermediate loop	Increase radiation field	Balanced coolant pressures in reactor and intermediate loops, SR&AA		
- Flow blockage on reactor side	Reduction/cessation of reactor cooling flow	None	Reduce reactor power SR&AA		
- Flow blockage on intermediate side	Increased temperature in reactor loop				
- Rupture of intermediate side			SR&AA		
• TEM pump failure in intermediate loop	Cessation of intermediate loop coolant flow Loss of reactor cooling Increasing reactor temperature		Activate redundant pump SR&AA		
- Failure of TE material or circuit.					
- Coolant channel weld failure			SR&AA		
• Failure or puncture of intermediate loop piping and accumulator					
• Failure of NaK-to-gas heat exchanger	Cessation of intermediate loop coolant flow Loss of reactor cooling Increasing reactor temperature				
- Leakage of NaK into gas					
- Breach of NaK side containment					
- NaK flow blockage	Reduction of intermediate loop cooling flow Increasing reactor temperatures		Reduce reactor power SR&AA		
- Breach of gas side containment	Loss of Brayton loop gas Loss of reactor cooling Increasing reactor temperatures				
- Inadvertent opening or leakage across isolation valves of redundant PCS's	Reduction of reactor cooling		Reduce reactor power SR&AA		
• Failure of Turbine					
- Loss of blade	Shutdown of Brayton loop and loss of reactor cooling		SR&AA Activate redundant PCS		
- Bearing failure					
- Shaft failure					
- Breach of turbine scroll					
- Loss of auxiliary cooling			Activate redundand PCS SR&AA		
• Failure of TAC compressor					
- Loss of blade			SR&AA Activate redundant PCS		
- Bearing failure					
- Shaft failure					
- Breach of compressor scroll			Activate redundant PCS SR&AA		
- Loss of auxiliary cooling					
• Failure of TAC alternator					
- Open or short in stator	Shutdown of Brayton loop and loss of reactor cooling		Activate turbine cutoff valve SR&AA Activate redundant PCS		
- Shaft failure			SR&AA Activate redundant PCS		
- Loss of auxiliary cooling			Activate redundant PCS SR&AA.		
• Breach of recuperator outer shell					
• Failure of Brayton loop waste heat exchanger					
- Breach of gas side containment	Shutdown of Brayton loop and loss of reactor cooling		SR&AA. Activate redundant PCS		
- Breach of coolant side containment					
- Gas to coolant leakage					
- Coolant side blockage	Increasing temperatures in Brayton and reactor loops		Reduce reactor power Activate redundant PCS SR&AA		
• Failure or puncture of Brayton loop piping	Shutdown of Brayton loop and loss of reactor cooling		SR&AA. Activate redundant PCS		
• Gas management system malfunctions and allows Brayton loop to vent					
• Failure of heat rejection pump					
- Open or short in motor stator	Increasing Brayton loop and reactor loop temperatures		Activate standby pump SR&AA Activate redundant PCS		
- Bearing failure					
- Seal failure					
- Internal leakage of NaK into stator					
- Loss of auxiliary cooling					
- Failure in seal leakage recirculation			Switch in standby power SR&AA.		
- *Loss of electrical power*					
• Failure in main radiator					
- Rupture of coolant channel	Increasing temperatures in the Brayton and reactor loops		Activate redundant PCS SR&AA.		
- Blockage of radiator feed line					
- Removal of emissivity coating			Reduce reactor power SR&AA		
• Thermal shroud covers main radiator			SR&AA Eject thermal shroud		
• Failure in secondary radiator					
- Rupture of coolant channel	Increased temperature in electronic and TAC components		Activate redundant PCS SR&AA		
- Blockage of radiator feed line					
- Removal of emissivity coating			Reduce reactor power SR&AA		
• Failure of secondary heat rejection pump, (all causes)			Activate standby pump Activate redundant PCS SR&AA		
• Rupture of secondary heat rejection piping or accumulator			Activate redundant PCS SR&AA.		
• Shield Failure					
- Rupture or puncture of lithium	None	None	Reduce power output of reactor	Increased radiation streaming through failed section.	
- Gross rupture of shield	Loss of shielding cooling Shield temperature increases Rupture of power system intermediate loop	Increased radiation field	SR&AA	Dissociation of all lithium hydride in shield Overtemperature meltdown of reactor components	Increased radiation field in all directions Release of fission products and/or activated coolant
• Shield Cooling Failure					
- Pump failure (all causes)	Shield temperature increases	None	Activate redundant pump SR&AA.	Dissociation of all lithium hydride in shield	Increased radiation field in all directions
• Coolant line puncture			SR&AA	Dissociation of all lithium hydride in shield	Increased radiation field in all directions
- Radiator failure					
• Failure of voltage control system					
- Low field excitation current	Overspeed of TAC unit. Shutdown of Brayton loop and loss of reactor cooling		Close turbine shutoff valve SR&AA.	Overtemperature/meltdown of reactor components	Release of fission products and/or activated coolant
- High field excitation current	Underspeed of TAC unit. Shutdown of Brayton loop and loss of reactor cooling		SR&AA		
• Fracture of all parasitic load resistors	Overspeed of TAC unit. Shutdown of Brayton loop and loss of reactor cooling		Close turbine shutoff valve SR&AA.		

* SR &AA = SHUTDOWN REACTOR AND ACTIVATE AFTERCOOLING

Any rupture of the reactor primary loop or any other loop in the power module that eliminates the ability to remove the generated heat in the reactor, makes immediate shutdown of the reactor mandatory to prevent overtemperature and physical damage to the reactor fuel elements.

If a leak occurs in the reactor primary-to-intermediate loop heat exchanger, then activated reactor coolant can be introduced into the intermediate loop. Since the intermediate loop extends outside the shield to the power conversion systems located at the interface of the Space Base and main radiator, a source of unshielded nuclear radiation is brought close to the Space Base. The quantity of activated coolant introduced into the intermediate loop can be limited by balancing the loop pressure levels to eliminate a pressure difference across the fracture in the heat exchanger.

The reactor coolant flow passages in any part of the reactor loop may become partially blocked because of accidental contamination, solidification of coolant contaminants or dissolved containment material, etc. If design coolant flow rates cannot be maintained, a reduction in reactor power level may be necessary to prevent deleterious temperature levels in the reactor fuel elements.

Two standby power conversion systems (PCS) are provided for each reactor in the reference power module, so any failure in an operating Brayton loop need only be a temporary loss of power until a redundant PCS is activated. If the Brayton system failure causes immediate and total loss of reactor cooling, then the reactor must be shutdown or at least set back in power level to the heat rejection capability of the aftercooling subsystem until the redundant PCS is activated (possibly 2 - 4 hours). If the Brayton failure is one that allows continued operation of the Brayton loop for a limited time, for example, loss of cooling to the TAC bearings, then the redundant PCS may be activated while the reactor is still operating.

It has been assumed that a turbine bypass valve and/or a cut-off valve is present in the Brayton loop-to-prevent drastic overspeed and possible physical breakup of the TAC unit,

in the event a failure within the electrical circuit of the alternator removes the alternator mechanical load from the TAC shaft.

Accidental removal of the thermal emissivity coatings on the power module radiators could seriously limit the safe operating power level of the power module if the emissivity of the radiator fin material were very low. The problem could be alleviated if the surface of the radiator material were treated to have a moderate value of ~ 0.5.

It has been assumed in this study that the configuration of the secondary cooling circuits are similar to the main heat rejection circuit, i.e., a single secondary radiator surface contains three separate cooling circuits, one for each PCS.

A puncture or rupture of the outer surface of the Lithium Hydride (LiH) shield may result in the local dissociation of the LiH and escape of the released hydrogen, dependent on the local shield temperature. The resultant "hole" in the hydride shield would be a source of an abnormally high neutron flux, thus increasing the neutron radiation dose rate in the direction of the "hole". The release of metallic lithium which accompanies the dissociation of LiH may gradually corrode the containment walls of adjacent sections of LiH if temperatures are $\geqslant 900\,^{\circ}K$ ($1200\,^{\circ}F$) thus propogating the failure and increasing the size of the shield "hole". Conceivably, this procedure could continue until the entire LiH shield section were disintegrated. These possibilities suggest design guidelines which would insure protection of the outer surface of the shield and/or limit the temperature in the outer shield regions to some low level to preclude or severely limit the dissociation of LiH in the event of a puncture. Also the assurance of shield cooling through redundancy of components and subsystems is another potential design guideline.

Failure of most of the components in the engine control and electrical control subsystems would not have a drastic effect on the operation of the power system. The two exceptions are:

1. Failure of the voltage control component which would result in either a very low or a very high field excitation current to the alternator. The resultant drastic overspeed or underspeed of the TAC unit would necessitate shutdown of the power module.

2. Fracture of all parasitic load resistors resulting in overspeeding of the TAC unit.

Table 7-3 presents the potential hazardous accidents to the power module which might occur in orbit during a normal power module startup. The accidents listed are in addition to the many failures within the power module that have already been listed in Table 7-2 and which also apply to the startup phase. None of the startup accidents identified would result in an immediate nuclear hazard.

During power module shutdown, the critical subsystem is the aftercooling subsystem as indicated on Table 7-4. If it fails, overheating and failure of the reactor fuel elements is possible.

In the prelaunch phases before launch, the main hazard from a nuclear viewpoint would be a NaK fire that would destroy the reactor and release nuclear fuel. As shown on Table 7-5, this hazard may be eliminated by containing the NaK in confined regions and blanketing it with inert gas. The same hazard exists during the atmospheric portion of the launch ascent phase (Table 7-6). It would probably be very difficult to extinguish the NaK fire with an inert gas blanket during this operation but once the launch vehicle rose above the Earth's atmosphere, the fire would extinguish due to the lack of oxygen and moisture.

For the power module disposal phase, the power module will be cool and inoperative if sufficient wait time was allowed. The prime nuclear hazard would occur if the reactor coolant loop were fractured to release fission products and activated coolant (see Table 7-7).

Design and Operations Guidelines pertaining to this analysis are contained in Section 7.2.2.

7.2.2 REFERENCE REACTOR POWER MODULE DESIGN AND OPERATIONS CONSIDERATIONS

Table 7-8 indicates the design considerations associated with the Reactor Power Modules, including the following subsystems:

Table 7-3. Power Module Accidents which may Result in a Nuclear Hazard

POWER MODULE STARTUP

Accident	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potential Nuclear Hazards
• Loss of electrical power	Loss of reactor cooling	None	Switch in alternate power source. SR&AA *	Overtemperature/melting of reactor components	Release of fission products and/or activated coolant.
• Thermal shroud can't be removed.			SR&AA		
• PCS system cannot be started.			Restart with standby PCS. SR&AA		
• Heat rejection radiator(s) are frozen.			Restart with standby PCS. Initiate emergency procedure for radiator heating. SR&AA		
• Isolation valves on redundant NaK-gas heat exchangers won't close			SR&AA		

* SR&AA = Shutdown Reactor and Activate Aftercooling.

Table 7-4. Power Module Accidents which may Result in a Nuclear Hazard

POWER MODULE SHUTDOWN

Accidents	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potential Nuclear Hazards
• Failure of shutdown control signal/ system	Reactor increases in temperature if PCS becomes inoperative.	None	None	Overtemperature/meltdown of reactor components	Release of fission products and/or activated coolant
• Failure of after-cooling system - Heat exchanger failures - Pump failures - Radiator failures - Piping failures	Reactor increases in temperature after shutdown.		Activate redundant aftercooling system or component		

* SR&AA = Shutdown Reactor and Activate Aftercooling

Table 7-5. Power Module Accidents which may Result in a Nuclear Hazard

PRELAUNCH MISSION PHASE

Accident	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potental Nuclear Hazards
• NaK spill during fill operation of all NaK systems.	Fire in power system vicinity	None	Flood area with inert gas. Quick drain of NaK systems to sump tank.	Meltdown of reactor fuel elements	Release of radio-active fuel material
• Failure or rupture of NaK containment after fill operation.					
- Primary reactor loop					
- Intermediate loop					
- Main heat rejection loop					
- Auxiliary heat rejection loop					
- Aftercooling loop					

* SR&AA = Shutdown Reactor and Activate Aftercooling

Table 7-6. Power Module Accidents which may Result in a Nuclear Hazard

LAUNCH AND ASCENT MISSION PHASE

Accident	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potential Nuclear Hazards
• Failure or rupture of NaK containment - Reactor loop - Intermediate loop - Main heat rejection loop - Auxiliary heat rejection loop - Aftercooling loop	Fire in power system vicinity	None	Flood area with inert gas. Quick drain of NaK system to sump tank.	Meltdown of reactor fuel elements	Release of ratio-active fuel material

*SR&AA = Shutdown Reactor and Activate Aftercooling.

Table 7-7. Power Module Accidents which may Result in a Nuclear Hazard

POWER MODULE DISPOSAL
MISSION PHASE

Accident	Operational Effect	Immediate Nuclear Hazard	Possible Sequence of Corrective Actions	Potential Nuclear System Effects if All Corrective Actions Fail	Potential Nuclear Hazards
• Puncture or rupture of reactor loop - Piping - Accumulator - Heat Exchanger	None	Release of fission products and/or activated coolant	None	Loss of reactor coolant	Release of fission products and/or activated coolant.

* SR&AA = Shutdown Reactor and Activate Aftercooling.

1. General PM including Power Conversion System (PCS)
2. Reactor/Shield
3. Reactor/Control
4. NaK Coolant Loops/Radiators
5. Reactor Disposal System

Section 5 of this volume indicated design and operational considerations associated with mission support activities. The data of Table 7-8 deals primarily with orbital considerations. In addition, Volume III of the study emphasizes terrestrial safety considerations.

7.2.3 POWER MODULE/SPACE BASE ALTERNATE CONFIGURATION EVALUATION

Six different power module/Space Base configurations were evaluated to assess the relative influence on nuclear safety for each configuration. The configurations evaluated are described below.

Configuration	Description
1 (Space Base Reference Design)	Two reactors, one on each of two booms at one end of the base with separation distance between reactors being ~ 30 m (100 ft).
2	Individual reactors located on booms on opposite ends of the Base.
3	Tandem reactors, in-line, each with its own radiation shield located on a boom at one end of the Base.
4	Tethered reactors located on opposite ends of the Base.
5	Two reactors, arranged side-by-side in an integral radiation shield located on a boom at one end of the Base.
6	Same as 5 except reactors are in-line instead of side-by-side.

Table 7-8. Power Module Design and Operations Guidelines

STATEMENT	REASON	REMARKS
GENERAL		
• Consider providing a pressurized and temperature controlled engine room	Facilitates repairs and minimizes crew exposure during maintenance duties	(See Section 7 3 3)
• Consider simultaneous operation of multiple PCS with each reactor	Maintains Space Base power level and dissipates reactor heat in event of one unit failure	Split normal load between PCS with PCS capable of operating at above normal power (see Section 7 1 3 2 4)
• Design repairable equipment on a "black box" modular approach	Facilitates repairs, and minimizes crew exposure during repairs	(See Section 7 3 3)
• Provide real-time back-up and alternate control and monitoring of power plant via ground control	Provides contingency capability	
• Consider a positive mechanical system for separating power module from Space Base	Allows reliable separation from base without rocket ignition 7.3 4	Provision could be made for separation of of Reactor/Shield from radiator or power module from the Space Base (see Section 7 3 4)
• Provide protection against fragmentation accidents	Minimize release of NaK, shield penetration in event of PCS accident (rotating machinery) or pad explosion	Consider relative location of machinery, tankage for protection of NaK lines and shield
• Provide rapid start-up capability of redundant PCS	Minimize temperature excursion and after heat cooling Minimum down-time	Consider automatic start-up equipment, heated coolant loops etc
• Provide turbine by-pass or cut-off valves in each PCS	To prevent drastic overspeed of breakup of TAC unit	(See Section 7 2 1)
• Provide dispersed parasitic load resistors	To preclude possible destruction of all resistors by a single accident	
• Provide an after-heat removal subsystem that has adequate heat rejection capability to limit the temperature rise in the reactor core to acceptable margins even after shutdown from emergency (600 KWt) operating conditions	Minimize core rupture and release of activated coolant	See Section 6 3 2 1, 7 2 1 and Volume III Part 2 Redundancy should be considered
• Consider use of shield meteoroid bumper	Protect against shield degradation and puncture	
• Provide a compartmentalized LiH shield	To limit the volume of hydride affected by a shield break	See Section 6 3 2 1 and 7 2 1
REACTOR/SHIELD		
• Design reactor to preclude criticality and excursion accidents	Most severe accident on Base is destructive reactor excursion	Reference ZrH reactor is relatively insensitive to criticality accidents (see Section 7 1 3 2 3)
• Provide means to insure neutron shield integrity	H_2 dissociates from LiH when exposed to space vacuum	Double containment and compartmentalized sealed sections would minimize the shielding loss due to puncture or leaks
• Provide instrumentation to detect LiH shield puncture	Early detection will minimize hazard	Pressure transducers in shield compartments would complement Radiological safety program sensors (see Sections 6 2 2 1 1 and 7 3 1)
• Consider a shield cooling system	Prevent LiH dissociation and loss of neutron shield effectiveness	Local temperatures in reference design range up to 900°K Additional reentry protection would aggravate the problem *(see Section 7 3 4) Temperatures should* be limited to ~ 550°K
• Review trade-off of reactor radiation shielding vs material radiation shielding	Natural environment much higher than reactor environment in reference design Possibility of reducing total dose within weight constraints	(See Section 6 2 1 1 1)
REACTOR/CONTROL		
• Consider a positive means for locking reactor control drums in least reactive position	Provides protection against ground transportation, launch installation and disposal criticality accidents	Consider remote operation rather than EVA (see Section 7 3 4 1 1)
• Provide an effective redundant and automatic means of shutting down the reactor in specific failure mode situations	To minimize reactor damage and extent of hazards due to massive failures, e g loss of coolant, collisions, shield damage, etc	Consider use of SCRAM mechanisms or similar features (see Section
• Provide a positive means for shutdown of the reactor after loss of electrical power	Reactor could continue to generate thermal power for some time after loss of power to actuators	Reactor control should be connected to back-up power supply
• Consider providing positive/permanent reactor shutdown at end of mission	To prevent possibility of reactor excursions	Control drum lockout and/or core poisons are possible candidates (see Section 7 3 4 1 1)
• Consider providing two independent means of sensing control drum position	Present pulse counting system would give false position indication in event of drive train failure	Assists in positive control and in start-up operations
• Provide coolant pump failure detection and automatic start-up of redundant pumps	Minimize reactor temperature excursion and increase lifetime of reactor	Minimizes hazards of coolant loop NaK release
• NaK inventory in reactor coolant loop should be as small as possible	To limit amount of activated coolant which could be released	See Seciton 6 3 2 1 and 7 2 1
• Failure of reactor coolant containment should be minimized by use of generous design margins, factors of safety, elimination of welds, etc	Minimize NaK coolant release	See Section 6 3 2 1 and 7 2 1
• Provide protection (heavy gamma shielding) in the shield cavity and gallery section	To minimize loop puncture by blast fragments and confine escaping activated coolant	See Section 6 3 2 1 and 7 2 1
• Consider operation of the reactor primary loop at a slightly lower pressure than the intermediate loop	A leak between loops in the heat exchanger would result in a coolant transfer from the intermediate loop to reactor loop rather than the reverse	See Section 6 3 2 1 and 7 2 1
• Consider use of an isolation valve across the gas sides of the accumulators which would automatically open to equalize the two loop pressures if a leak occurs across the heat exchanger	Minimize release of activated coolant	See Section 6 3 2 1 and 7 2 1
• Provide isolation valves on both sides of each NaK-to-gas heat exchanger	To minimize release of activated coolant	Actuation of the valves should be such that electrical power is required to open or close the valve
• Provide stand-by power supply capability for each coolant pump requiring electrical power	To reduce temperature excursions and after heat removal requirements	See Section 7 2 1
• Treat Radiator substrate materials for highest possible thermal emissivity consistent with application, adhesion, life, etc	Maintain reasonable operating power levels and efficiances	See Section 7 2 1
NaK COOLANT LOOPS/RADIATORS		
• Provide meteorite puncture protection for NaK coolant lines	Minimize probability of release of fission products, activated/non-activated NaK	Plumbing in gallery section is exposed in the reference design
• Provide redundant, non-repairable design philosophy for NaK loop plumbing	Precludes loss of coolant accident and in conjunction with 19 minimizes NaK leak hazard	NaK lines not repairable in space (see Section 7 3 3 and 6 2 1 1 2)
• Consider means to minimize the release of NaK in event of leaks	Minimize NaK release hazard	Double containment and isolation valves should be considered (see Section 6 2 1 1 2)
• Provide pressure and flow measurements in coolant loops to aid in NaK coolant release detection	Minimize NaK release hazard, allow implementation of emergency procedures	Effective in conjunction with Item 18
• Consider implementation of a NaK loop/ *reactor separation interface*	Minimizes transportation, handling, pre-*lauoch, disposal and replacement hazards*	Separable heat exchanger should be con-*sidered (see Section 7 3 3 and Section* 7 3 4 also Volume IV, Reference 7-7)
• Consider use of non-liquid metal radiator where performance requirements permit	Minimizes the liquid metal inventory and associated hazards	Applicable to Brayton and Organic ranking cycles
• Consider implementation of an independent reactor decay heat removal system	Provides for dissipation of reactor heat in event of loss of coolant and therefore reactor meltdown and release of fission products and activated material	Reference design is marginal at 330 kw(t), higher power levels would require the system
DISPOSAL SYSTEM		
• Provide an effective reactor reentry and impact protection system	Minimize hazard to earth's populace	Reference configuration may not survive some reentry modes if LiH is relied upon as reentry protection (see Section 7 3 4)
• Provide tracking and impact capability in event of reactor reentry	Minimize hazard to general populace	Effective for reservoir impact identification Consider transponders, pingers, dye markers (see Section 7 3 4)
• Provide safe, prompt disposal of spent or malfunctioning reactor	Minimize hazard to earth's populace and to Space Base crew	(See Section 7 3 4)

Table 7-9 presents a summary and discussion of the effects on nuclear safety for each configuration. One can conclude, from Table 7-9, that configuration (2) appears to be a very attractive consideration. However, final judgment must factor in the effects of system performance. For example, note that this configuration has significant nuclear safety advantages for all operations; however, two of these functions, orbital and rendezvous operations, impose performance penalties in the form of increased shield weight. The increased shield weight would be required to protect crew, instruments, and experiments which are sensitive to neutron and gamma radiation which would now emanate from both sides of the Space Base. Rendezvous and logistics transfer functions would also be affected. The reduced approach corridor for rendezvous resulting from reactors located on each end of the Base should be factored into future performance trade-offs.

7.2.3.1 Conclusions

The reference design, Configuration (1) offers significant nuclear safety advantages for the intended mission. Configuration (2) can provide an increased safety margin at the expense of increased shield weight, due to the increased isolation of each reactor and should be evaluated for future design and performance interactions.

7.2.4 Alternate Power Conversion Systems

The effects on nuclear safety by substituting the following power conversion system candidates are presented.

1. Mercury Rankine
2. Organic Rankine
3. Compact Thermoelectric Converters
4. In-Core Thermionic

These systems were compared to the reference Brayton system. The ZrH reactor was assumed to be the power source except in the case of the in-core thermionic, where a fast reactor is employed.

Table 7-9. Power Module Configuration Trade-Off Influence on Nuclear Safety

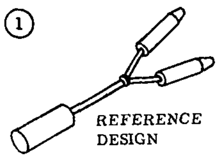
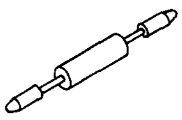
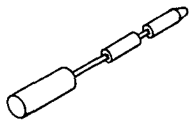
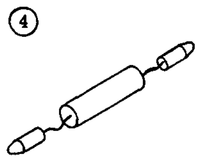
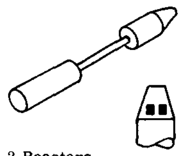
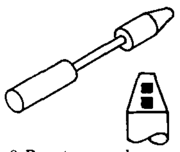
Operational Function	①  Reference Design - 2 reactors, Y configuration	②  2 Reactors - at opposite ends of base	③  2 Reactors - power modules in tandem	④  Tethered reactor power modules	⑤  2 Reactors - close coupled, side-by-side	⑥  2 Reactors - close coupled in tandem
Launch	Reactors may be launched separately thus minimizing potential nuclear safety hazards such as fire, water immersion, accidental excursions, etc	Same as ①	Same as ①	Same as ①	Reactors must be launched together, greater potential nuclear safety hazards as cited in ① because same abort accidents involve two rather than one reactor	Same as ⑤
Power Module Installation and Buildup	Reactor power modules may be installed at separate times Greater danger of release of activated products if 1st module has been operated Radiation hazard exists from reactor if it is operating during installation of 2nd reactor module	Low hazard potential, affords large safety margin if one reactor is operating while 2nd is being installed on opposite end of base	Low hazard potential if both modules are installed cold Radiation hazard if 1st reactor has been operated and greater potential hazard from release of activated products Installation of 2nd module impractical if 1st is operating	Moderate hazard potential if 1st module is operating when 2nd is installe installed Module must be rotated around base to maintain separation distance	Only one installation is necessary However, accidents arising from installation could double the nuclear safety hazards since two reactors are involved	Same as ⑤
Power Module Startup	Low hazard potential	Same as ① Startup accidents initiated by nuclear or non-nuclear sources will not effect 2nd power module	Moderate hazard potential Nuclear radiation from inboard reactor could effect PCS instrumentation on outboard unit Increased shield can reduce or eliminate this problem	Same as ①	Stuck thermal shroud or frozen radiator creates a hazard from both reactors Nuclear coupling of reactors complicates startup procedures Possible interference between reactor instrumentation	Same as ⑤
Orbital Operations (Thermal Effects)	Low possibility of a failure in one reactor system affecting the other reactor system	Very little possibility of a failure in one reactor module impacting on other reactor module Increases hazard to experiments, equipment, etc Sensitive to nuclear radiation due to proximity of both reactors to base Eliminated by increasing shield mass	Same as ⑤	This configuration has the additional hazard of a potential mechanical separation of power module and base Possibility exists that reactor may still be operating when tether fails Separation distance must be maintained by rotating power module around the base	Single accident may result in destruction of both reactors with double the potential hazard	Same as ⑤
Rendezvous Operations	Only slightly more hazardous than close coupled reactor configurations Possibility exists that single collision could involve both reactors with resultant hazards of release of fission products, activated coolant and possible reactor excursions	Approach corridor reduced Single accident will probably effect only one reactor Increase in shield mass required to protect rendezvous crews	Same as ⑤	Rendezvous vehicles present serious hazard to tethered systems, cables, etc and vice versa rotation of both power modules necessary to maintain separation distance	Very little interference with rendezvous paths Possibility of low radiation levels for rendezvous paths and docking ports However, single collision could involve both reactors with resultant hazards of release of fission products and activated coolant and possible reactor excursions	Same as ⑤
Power Module Shutdown	Low hazard potential	Low hazard potential	Dependent on relative locations of the two reactors, operating module could influence shutdown module as per closed couple modules	Separation of tether could result in reactor remaining in orbit, not connected to space base, but still operating	Nuclear coupling may generate significant power in shutdown reactor from operating reactor This could be hazardous if afterheat cannot be removed Meltdown failure of one reactor could destroy integrity of operating reactor	Same as ⑤
Power Module Repair	Extra shielding may be needed to allow repair of failed system while 2nd system is operating Little effect on repair function (see Section 7 2 3)	Operating module has no influence on repair of failed module	Repair of outboard module is impractical PCS repair feasible on inboard module only	Radiation levels around a shutdown module may be too high for repair operations since shielding requirements for normal operations are not as stringent as other configurations due to increased separation distance	Repair of failed reactor precluded if 2nd reactor is operating because of hazardous nuclear and thermal environment Both reactors must be replaced leaving base on emergency power	Same as ⑤
Power Module Replacement	Replacement of one power module is feasible while other is operating Radiation levels from operating reactor are relatively low See Section 7 2 3	Operating module has no effect on replacement of failed module	Replacement of complete outboard module possible but only if inboard module is shutdown Replacement of both modules required if inboard module fails	Radiation levels around a shutdown module may require a specially shielded or remotely operated tug for replacement Assumes less reactor shielding required for this concept due to increased separation distance between reactor and base	Only the complete replacement of both reactors is feasible	Same as ⑤
Power Module Disposal	Separate disposal of each module can be accomplished Very little interaction between modules	Reactors may be disposed with little or no effect on remaining power module	Oversized disposal engines needed for each power module in case modules cannot be separated and must be disposed as one unit In the event this abort situation occurs, one must consider that nuclear safety hazards now involve two rather than one reactor Premature failure of inboard module requires replacement and shutdown of both modules	Separate disposal of each module is possible However perturbations in flight mechanics of base and 2nd power module will result when first or second module is disposed	Larger thrust engines required Greater potential hazard if disposal system fails since it involves two reactors All abort situations must consider the resultant nuclear safety hazards of two reactors rather than one	Same as ⑤

Table 7-10 represents a comparison of the effects on nuclear safety for each of the alternate power conversion systems studied and a relative ranking for each configuration. One can conclude from this table that the Organic Rankine system and the reference Brayton system are equally attractive. The lower operating temperature of the Organic Rankine System is a significant feature which provides reduced thermal stress and material compatibility problems. In addition, the greater temperature margin between the fuel clad nominal operating temperature and its melt temperature is a very attractive safety advantage; the Organic cycle operates at a reactor outlet temperature of 750^{o}K as compared to 950-1000^{o}K for each of the other systems studied. The relatively high efficiencies, 20-30%, and hence lower reactor power for the Brayton and Organic systems result in lower fission product and activated coolant levels. The high efficiency also reduces the amount of after-heat which must be dissipated after the reactor is shut down.

The working fluid, a Helium-Zenon gas and organic fluid, for the Brayton and Organic systems respectively, are non-toxic, non-corrosive and as such are very important considerations wnen planning the repair, maintenance and disposal operations. Their inert characteristics are very desirable as related to nuclear safety. The potential degradation of the organic fluids when subjected to long term radiation has not been considered in this analysis, but should be factored into the final selection process.

The remaining alternate PCS', the Thermoelectric, Mercury Rankine and In-Core Thermionic, have several specific features which make them less desirable from a nuclear safety aspect. Their relatively low efficiencies, 5-13%, result in higher fission product and activiated coolant inventories. Each of these systems have caustic and/or toxic working fluids in the PCS loop which tend to increase the corrosion/erosion rates and also significantly reduce the possibility of performing PCS repairs.

Static systems such as thermoelectrics and thermionics are often considered attractive due to their inherent multiple redundancy. However, when the repair function is evaluated from a nuclear safety aspect it becomes quite evident that significant nuclear safety disadvantages exist. For example, NaK leaks which could develop in the Thermoelectric System Compact

Table 7-10. Relative Influence of Alternate Power Conversion Systems on Nuclear Safety

Operational Phase	① Reference Design - Brayton PCS	② Mercury-Rankine PCS	③ Organic-Rankine PCS	④ Compact Thermoelectric Converter	⑤ In-Core Thermionic Reactor
Prelaunch and Launch Ground Operations	Primary and heat rejection loops contain NaK Potential *nuclear hazard due to* NaK fire	Mercury toxicity presents problems in addition to hazards *of NaK cited in* ①	Same as ①	Conversion system also contains NaK thus increasing the potential energy released during a NaK fire	Same as ④ Cesium in diode could present additional problems
Orbital Build-Up Power Module Installation and Buildup	PCS installed in power module on ground Power module attached to Base as a complete unit	Same as ① Release of toxic mercury could create safety hazard	Same as ①	Same as ①	Same as ①
Power Module Startup - Required reactor temperature for PCS startup	Operational temperature	Same as ①	Same as ①	477°K (400°F) lower than operational temperature	Same as ①
- Efficiency and its effect on fission product and activated coolant inventories	~ 20-30% High efficiency reduces reactor power and hence fission product and activated coolant inventories	~ 8-12% Low efficiency increases reactor power and hence fission product and activated coolant inventories	~ 20-30% Same as ①	Less than 10% Same as ②	~ 10-12% Same as ②
Orbital Operations Power Module Operation - Reactor coolant temperature	950°K (1250°F) Higher temperature levels relative to Organic Rankine system, inherently result in decreased reliability due to increased thermal stress and material problems Additionally less safety margin is available between nominal operating temperature and maximum fuel clad temperature Higher temperature also increases hydrogen loss rate from fuel and hence decreases reactor life	955°K (1260°F) Same as ①	755°K (900°F) The lower temp for this PCS will result in -Lower fission product and hydrogen pressures in fuel elements -Greater clad strength -Lower thermal stresses during emergency power transients -Greater strength in coolant containment components -Lower corrosion/erosion rates in reactor loop	950°K (1250°F) Same as ①	1000°K (1350°F) Same as ①
- Reactor power level to generate 50 kWe and its effect on temperatures, after heat and fission product and activated coolant inventories	330 kWt The low power level will result in -Lower inventory of fission products @ any time -Less afterheat or operating power to dissipate in emergency, less probability of core over temperature or melting -Lower ΔT in fuel element -Smaller coolant and components with less activated coolant	~ 425 kWt (Late 1970 technology) Moderate increase in nuclear safety hazards relative to the Brayton system due to increase in reactor power	~ 330 kWt Same as ①	~ 805 kWt (Late 1970 technology) This power level would require 2 operating ZrH reactors to generate 50 kWe Nuclear hazards greatly increased during all mission phases due to doubling of the number of reactors required to produce the same amount of power as in cases ①②, and ③	~ 535 kWt Higher power level increase fission product inventory level of activity in coolant and ration environment Hence, a decrease in nuclear safety One must also consider that another reactor must be installed if the criteria is to provide complete redundancy This would result in increasing the nuclear hazards
- PCS maximum temperature effect on reliability	866°K (1100°F)	939°K (1230°F)	644°K (700°F) Relatively low temperature should increase PCS component life thus lessening probability of failure and potential hazard from reactor	~ 880°K (~1125°F)	~ 1922°K (~ 3000°F) *(emitter)* Very high diode temperatures limit life of individual diodes Re-*lease of fission products* from fuel is more likely
- Number of PCS units per reactor, operating/standby Effect on after heat and power dissipation	1/2 Loss of a power conversion unit necessitates an immediate cut-back in reactor power and/or a method be provided to dissipate the reactor power and also after heat to preclude over-temperaturing of fuel elements	1/1 Same as ①	1/2 Same as ①	~ 20,000 Slow degradation of power with time rather than abrupt failure No effects on reactor conditions After heat is not a problem as long as coolant flow can be maintained	~ 100 Same as ④ Some localized fuel overheating with diode failure Possible fission product release
- Working fluid material effects	Inert gas No corrosion of PCS components	Mercury vapor Possible corrosion of PCS components inducing failure with resultant nuclear hazard	Organic vapor Same as ①	NaK as heat transfer agent in conversion loop Same as ②	NaK used in all loops Cesium vapor in conversion diodes Same as ②
- Configuration effects	Low heat transfer coefficients with large, vulnerable PCS components	High heat transfer coefficients with small components	(Same as ①)	(Same as ②)	(Same as ②)
Normal Power Module Shutdown	PCS shutdown presents no significant problems Provisions must be made for removal of decay heat	Same as ①	Same as ①	Greater flexibility in shutdown system Power can be decreased gradually due to inherent design After *heat does not re*quire special heat removal systems	Same as ④
Emergency Power Module Shutdown - Effect on temperature	High reactor temperatures result in higher thermal stresses in fuel and coolant containment during shutdown	Same as ①	Lower PCS temperatures result in lower reactor operating temperatures and hence greater safety margin, i e , fuel clad operating temp is lower resulting in a significant Δt margin relative to clad	High reactor temperature as in ① Loss of secondary cooling requires dissipation of reactor heat of almost twice the value of Brayton and Organic PCS's	Approx 200 more kWt of heat to dissipate than organic and Brayton PCS' The normal emitter operating temperature of ~ 1922°K (3,000°F) is critical factor to consider for over-temperature conditions
- Effect on afterheat	Low operational power results in less afterheat removal required	Same as ④	Same as ①	High operational *power results in* significant amount of after heat to be dissipated	Same as ④
- Possible means to reduce over pressure	Rapid shutdown of PCS possible by venting PCS working fluid	Venting of PCS fluid not practical because of mercury toxicity	Same as ①	(Not Applicable) NaK cannot be vented	Same as ④
Rendezvous Operations	Intermediate radiator area size	Same as ①	Large radiator area could reduce approach corridor	Very large radiator area req'd plus 2 reactors makes this PCS much more hazardous from a collision standpoint	Very small radiation area Lowest collision probability during rendezvous
Power Module Repair - Feasibility of repair	Repair of PCS possible, due to inert working fluid Low radiation dose from operating reactor due to high efficiency and lower power levels	PCS repair impractical because of toxicity of mercury working fluid	Same as ①	Repair of compact converter and piping impractical because of NaK coolant Redundancy of thermoelectric elements may preclude non "leak" type repairs	Entire reactor must be *replaced in case of* massive failures
- Feasibility of heat rejection loop repairs	Repair of components exclusive of PCS impractical because of NaK coolant	Same as ①	Repair of heat rejection loop components possible if organic fluids are used as coolant (jet condenser)	Same as ①	Same as ①
End of Mission Power Module Replacement - Theoretical reactor life (ZrH Reference Reactor) Effect on replacement frequency	~ 9 6 years Long reactor life results in decrease in replacement and disposal frequency and hence decrease in hazards associated with these functions	~ 7 5 years (Late 1978 technology) Not as desirable as Brayton	> 10 years Same as ① Potential degradation of organic fluid is not considered	~ 3 5 years Short reactor lifetime requires frequent replacement and disposal Hence, nuclear safety hazards are increased	4 5 years (fast spectrum reactor) Same as ④
- Probability of PCS replacement	Replacement of power conversion system due to multiple PCS failure is possible	Impractical due to toxicity of Mercury and possible contamination of Engine Room	Same as ①	Very low probability of conversion unit failure requiring power conversion system replacement	Low probability of a conversion unit failure requiring total power system replacement can tolerate ~ 10% failure of total number of diodes
- Feasibility of PCS replacement	Replacement of PCS is possible	Replacement of PCS impractical because of toxicity of Mercury working fluid	Same as ①	Replacement of compact converters not practical because of high radiation levels in gallery and because of NaK coolant	Impossible - entire reactor and PCS may be replaced
- Feasibility of PCS component replacement	Replacement of PCS components is possible	Same as above	Same as ①	(Same as above)	Not feasible PCS is integral part of the reactor
Power System Disposal - Effect on disposal frequency	Moderate number of disposals theoretically required	(Same as ①)	Theoretically, few disposals necessary due to high efficiency and low temperature/power operation	Increase in nuclear safety hazards due to greater frequency of disposal and fact that two reactors instead of one must be disposed of	Same as ④
- Fission product and activated coolant hazards in event of accident	Low fission product and activated coolant inventories in reactor loop	Higher fission product and activated coolant inventory than ① and ③	Same as ①	Very high fission product inventory and activated coolant due to low efficiency, increases nuclear safety hazards	Same as ②

Converter or its associated piping would probably result in system shutdown. This failure is considered unrepairable whereas piping leaks (He-Xe gas) in a Brayton system probably can be repaired. If the NaK leak were of significant size it could contaminate the entire engine room equipment. The power conversion diodes in the thermionic reactor cannot be repaired since they are an integral part of the reactor. For the out-of-core thermionic reactor, diode repair is also considered impractical due to the use of NaK or Li as the heat transfer medium.

CONCLUSION

The reference Brayton system appears to be an ideal selection as the power conversion system from a nuclear safety aspect. The Organic Rankine is equally as acceptable on the basis of nuclear safety.

7.2.5 ALTERNATE POWER REACTORS

The results presented in this section only represent a summary of the work performed due to the classified nature of the study. The detailed information supporting these results is presented in Appendix F (Volume II, Part 2).

A number of different reactor designs have been proposed as the nuclear heat source in a space vehicle electrical power generation system. A few of these reactor concepts have progressed to the fuel element development stage and the Zirconium Hydride (ZrH) reactor (SNAP-8) has been built and tested. An advanced Zirconium Hydride reactor design is the reference system for the Phase A Space Base Studies. However, final selection of the reactor type will depend on future studies on performance, development cost, and relative nuclear safety. An initial evaluation of nuclear safety has been made and is presented in this section and in Appendix F. Its purpose is to compare actual and potential safety problems so that appropriate analysis can be performed and nuclear safety can be considered in the final selection of the reactor design for future programs.

The comparison of nuclear safety has been made as a function of reactor type, with reactors being typed as either "thermal" or fast, depending on the predominate energy of the neutrons triggering the fission process. The zirconium hydride reactor (SNAP-8) is an example of a

"thermal" reactor for space power application while the Advanced Reactor Design of NASA-Lewis (Reference 7-1) is typical of "fast" reactors being developed for generating electrical power in space. The comparisons are qualitative only, and have been obtained by examining a number of space reactor designs and determining their characteristics in regard to nuclear safety. These considerations were then applied to the Reference Zirconium Hydride (ZrH) Reactor design and the NASA-Lewis Advanced Reactor (AR), in all the Space Base mission phases. The ZrH thermal reactor system was assumed to generate 100 kWe, while both 100 kWe and 300 kWe designs were considered for the AR fast reactor systems.

The safety aspects of the ZrH thermal reactor and the AR fast reactor are listed below in the order of decreasing nuclear hazard. The order presented is somewhat subjective because of the qualitative nature of the safety evaluations and the lack of complete information on the probabilities of occurrence for the various accidents.

1. The ZrH system has a nuclear safety advantage in that it will not melt from self-generated heat. If it should melt because of the external environment, it would not form a nuclear reactive configuration. In contrast, under certain conditions, the AR fast reactor will melt from self-generated heat and could form an uncontrollable critical mass, generating about one hundred times greater than normal thermal power, at temperatures of about 3030°K (5000°F).

2. The compression of a shutdown ZrH thermal reactor into a compact, voidless mass will not initiate a sustaining nuclear reaction but a similar compression of the AR fast reactor could produce an uncontrolled critical reaction. The probability of experiencing such a reactor compression in orbit is remote. The probability of attaining the required compression in an Earth impact is yet to be determined.

3. Under certain conditions, the penetration of water or other hydrogeneous liquid into the ZrH thermal reactor can produce a supercritical condition, although the probability of achieving the required rate of liquid injection seems remote. In contrast, the same material inserted into the AR fast reactor lessens its reactivity. This contrasting response to hydrogeneous material may be important, in the event of an accidental return to Earth of a reactor and a subsequent impact and submersion in a body of water.

4. The prompt neutron lifetime and prompt period of the ZrH thermal reactor is approximately two hundred times longer than the corresponding times in the AR fast reactor. The respective reactor control systems will be designed with response times to match the different neutron time characteristics. Therefore,

under normal conditions, the difference is of little consequence. However, if accidental prompt criticality occurs, the peak power and the total excursion energy released in the AR fast reactor could be orders of magnitude greater than in the ZrH thermal reactor.

5. The core components in the AR fast reactor have a much higher temperature capability than corresponding ZrH thermal reactor components. This capability will probabily allow the AR reactor to absorb, without damage, a range of accidental increases in power and temperatures, which otherwise, would disable and release fission products from the fuel elements of the ZrH thermal reactor.

6. The reported "design" life for the AR fast reactor is five years and the same lifetime has been assumed for the ZrH thermal reactor in this study. However, the energy generation capability of the AR reactor in terms of megawatt-hours is about three times greater than that of the ZrH reactor. Since the AR power system is more efficient due to its higher operating temperature levels, its potential lifetime capability is approximately 4.5 times longer than the ZrH thermal reactor (when both systems are operated at 100 kWe). When the AR system is operated at 300 kWe, its potential lifetime is still 50% longer than the ZrH operating at 100 kWe. Thus, fewer replacement/disposal operations, with their inherent hazards, may be required with the AR system. However, the AR reactor has a nuclear safety disadvantage.... Although its potential lifetime is greater, the inventory of fission products (which are approximately proportional to lifetime/energy generation) that could be released in a replacement/disposal accident, are correspondingly greater.

7. The higher temperature capability of the AR fast reactor is reflected in higher power conversion efficiency and lower operating thermal power levels for equivalent electrical output. The nuclear safety advantages of the lower power level are somewhat offset by the greater failure probability in the power conversion components due to the higher temperature levels. The net comparison of relative nuclear safety will depend on the failure rate characteristics of the power system components at the different temperature levels.

CONCLUSIONS

In general, the ZrH reactor has some inherent characteristics, i.e., strong negative temperature coefficients, low void fractions and a contained hydrogen moderator which all contribute to providing significant nuclear safety advantages. Although the AR (fast reactor) does provide greater safety margins in some areas, its nuclear safety characteristics are not as dominant as those of the ZrH reactor.

7.2.6 ALTERNATE POWER CONVERSION SYSTEM CONFIGURATIONS

The influence of the PCS configuration on nuclear safety was evaluated for four different conditions:

1. Variable PCS configuration and operating conditions.
2. Separate versus integral heat exchangers.
3. Multiple (redundant) versus integral NaK loops.
4. PCS location relative to the reactor.

The effect of excess power generation capability, a power conversion unit being able to operate at twice its normal output (25 kWe to 50 kWe), was also assessed. Each of the configurations evaluated is illustrated in Figure 7-1.

Table 7-11 contains a summary of the nuclear safety considerations for each of the PCS configuration options as a function of mission phase. Further delineation of the various arguments is presented below for each configuration.

7.2.6.1 Variable PCS Configuration and Operating Conditions

7.2.6.1.1 Single vs Multiple PCS Operation per Reactor

With a single operating PCS per reactor, any failure in the PCS requires an immediate shutdown of the reactor to prevent high temperature which could damage the fuel elements. A reactor shutdown is a potential nuclear hazard because of the possibility of a reactor control system failure preventing shutdown, a failure in afterheat removal or localized fuel clad failure due to the shutdown temperature transient. Multiple operating PCS' eliminate the need for a reactor shutdown if one PCS fails, because the remaining PCS(s) continue to provide a cooling function for the reactor. Reactor temperature levels can be maintained by a setback in reactor power and flow rate, or gas pressure levels can be increased in the operating PCS(s) to utilize the full reactor power. The important point is that one possibility of a potential shutdown accident has been removed.

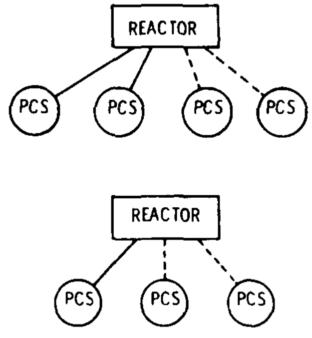
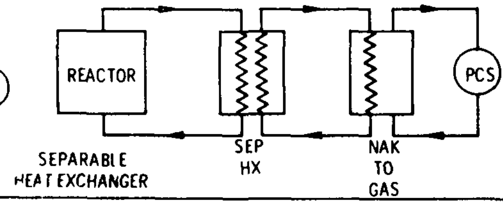
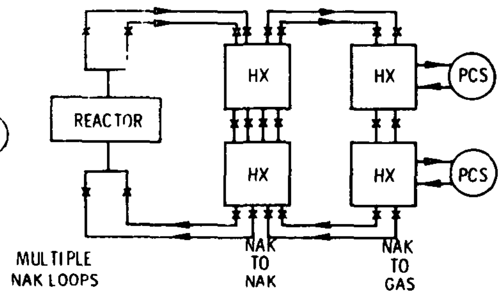
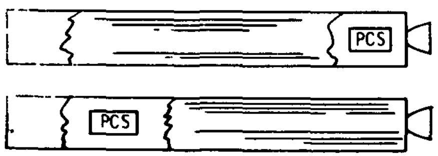
CONFIGURATION		COMMENTS
1	 SINGLE PCS OPERATION	REQUIRED POWER MODULE POWER 50KWe MODE OF OPERATION TWO PCS'S OPERATING AT 25KWe EACH TWO ON STANDBY EACH UNIT CAPABLE OF 50KWe OPERATION REQUIRED POWER MODULE POWER 50KWe MODE OF OPERATION ONE PCS OPERATING AT 50KWe TWO ON STANDBY RATED AT 50KWe EACH MAXIMUM POWER PER PCS IS 50KWe
2		SEPARABLE HEAT EXCHANGER REQUIRES ADDITIONAL COOLANT LOOP INCREASES ORBITAL LIFE OF DISPOSED SYSTEM
3		MULTIPLE LOOPS INCREASES NUMBER OF VALVES IN SYSTEM HENCE, RELIABILITY IS AFFECTED INCREASES POWER MODULE LIFE AND ABILITY TO PROVIDE FOR EMERGENCY COOLING
4	 PCS LOCATION	PCS REPAIR AFFECTED BY SEPARATION DISTANCE FROM REACTOR INCREASED SEPARATION DISTANCE IMPROVES REPAIR POTENTIAL

Figure 7-1. Alternate PCS Configuration

Table 7-11. Power System Configuration Option

Mission Phase	① Single vs. Multiple Operating PCSs per Reactor	② Single vs. Multiple Redundant PCS's per Operating PCS	③ Additional Power Generation Capability per PCS	④ Separable Heat Exchanger	⑤ Multiple Reactor Primary & Intermediate Loops
Prelaunch/Launch	-Larger number of liquid metal loops with multiple PCS's ∴ greater probability of a spill and fire (not applicable if NaK only in primary loop)	-Same as ①	-No effect on safety	-Improves Shipping -One additional liquid metal loop needed. Greater spill and fire probability	-Same as ①
Power System Installation and Startup	-No effect on safety during installation -Startup procedure more complex for multiple units. Reactor output must be distributed in a variable manner between operating PCS and PCS being started -Phase synchronization of of multiple PCS's per reactor only slightly more hazardous than phase synchronization of single PCS's from two reactors.	-Same as ① -Slightly greater probability of system non-start with multiple redundant units because of greater number of isolation valves in intermediate loop This effect is multiplied if more than one PCS per reactor is started.	-Power system size will be bigger for additional power capability ∴ slightly greater hazard during docking and installation -No effect on safety during startup.	-Same as ① -No effect on safety during startup.	-Same as ① -Similar to ②
Normal Orbital Operations	-Dependent on PCS design, multiple units may require a higher reactor output power with its attendant safety disadvantages. -Greater probability of control system failure with multiple PCS's because of complexity. Control system must balance both input and output power in all operating PCS's.	-Slightly greater failure probability as described above	-The larger radiator needed for additional power generation capability results in higher operating efficiency ∴ lower reactor power, lower fission product inventory and longer core life during normal operations.	-Increased reactor power with more fission products, less life, etc , required to offset thermal losses and temperature drop of separable heat exchanger -One extra circulatory loop increases failure probability -Separable heat exchanger is a barrier preventing fission products or activated coolant from reaching the PCS	-More components, greater complexity in heat source heat exchanger and greater probability of loop failure for multiple design.
Emergency Orbital Operations -Reactor failure	-Essentially no difference between single and multiple units unless aftercooling scheme uses primary cooling circuits Then safety advantage is with multiple units.	-No effect on safety	-Remaining reactor increases power output ∴ its relative nuclear safety decreases (less life, more fission products, etc.)	-No effect on safety	-Same as ①
-Reactor loop failure	-No effect on safety	-No effect on safety	-Same as above	-No effect on safety	-Fission product and/or activated coolant transport to PCS can be limited by shutting down failed loop and activating alternate loop(s) -Breach or failure of reactor intermediate loop can be circumvented by activation of alternate loop thus preventing nuclear hazard in reactor due to loss of coolant or cooling
-Intermediate loop failure	-Same as "reactor failure" above	-No effect on safety	-Same as above	-Greater probability for this failure since there are two intermediate loops, one on each side of the separable heat exchanger	-Same as above
-PCS failure	-With multiple unit configuration, a PCS failure does not completely eliminate reactor cooling. Also, subsequent to a PCS failure, a redundant unit can be activated without a reactor system startup.	-Continued operation of a particular reactor power system greatly enhanced by multiple redundant PCS's. Corresponding decrease in nuclear hazards due to replacement/disposal of failed power system	-With multiple operating PCS's this capability limits temperature changes in reactor. ∴ less probability of fuel clad damage and fission product release.	-No effect on safety	-No effect on safety
Rendezvous Operations	-No effect on safety	-No effect on safety	-With additional power generation capability, power system radiator will be larger. Rendezvous corridor could be affected	-No effect on safety	-No effect on safety
-Power System Repair	-Multiple units may present a slightly greater nuclear hazard during repair operations if fission products and/or activated coolant have leaked into intermediate loop, however redundancy could preclude necessity for repairs	-No effect on safety	-Radiation levels will be slightly higher in PCS compartment when either reactor system is operating at emergency power levels.	-Separable heat exchanger is a difinite nuclear safety advantage during repair operations since it precludes leakage of fission products and/or activated coolant into PCS compartment.	-Multiple loops provide nuclear safety advantage during repair because leakage of fission products and/or activated coolant into PCS compartment can be limited by use of redundant loop(s). -No effect on safety
-Replacement	-No effect on safety	-Multiple redundant PCS's preclude premature system replacement because of PCS failures.	-Replacement operation slightly more difficult and hazardous due to larger radiator area. -If power system has been operated at emergency power for a significant period of time, its inventory of fission products, hence its relative nuclear hazard, is greater.	-Allows individual replacement of either reactor only or PCS radiator system only. Ability to replace PCS only may limit number of reactor disposals required -Possibility of breaching coolant loops during separation operation. Potential release of fission products and/or activated coolant.	-No effect on safety
Power System Disposal	-No effect on safety	-Multiple units will limit number of disposal operations (see above).	-Disposal of slightly larger system should have negligible effect on nuclear safety -Potentially greater disposal hazard due to larger fission product inventory if system has been operated at emergency power.	-Number of reactor disposals would be limited to minimum number. Disposal of reactor shield assembly only may be less hazardous than disposal of complete power system -Decreased disposal payload -Increase in orbital life time for transfer to high earth orbital mode	-Disposal frequency could be reduced

Multiple operating units per reactor will require more complex engine and electrical control systems. This complexity is a matter of degree, since even with a single operating PCS per reactor, startup, shutdown, phase synchronization and load sharing control problems exist, when multiple reactor power modules are used. With multiple PCS units, the control procedures would be the same, but the logic and control circuits would be more complicated.

7.2.6.1.2 Single vs Multiple (Redundant) PCS'

The operating life of a Brayton power conversion loop is expected to be approximately 2-1/2 years, which is half the expected 5 year life for the reactor. Consequently, at least one redundant PCS per operating PCS is required if the power module life is to equal the expected reactor life. However, premature failure of the redundant PCS could require early replacement of the power module even though the reactor is capable of continued power generation. Since replacement and disposal is probably the greatest potential nuclear hazard associated with the Space Base power module, any design, procedure or method that limits the replacement/disposal operation to those due to reactor failure only, improves the nuclear safety of the power module. Multiple redundant PCS' is one such design configuration. The greater the number of redundant PCS', the greater the probability of attaining a total power module life equivalent to the reactor life.

The main disadvantages of multiple redundant PCS' are the many ancillary loops, and components required in addition to a more complicated control system. This added complexity may reduce the achievable reliability of the power system thus negating to some degree the safety advantage of the added PCS'. When the control system has been better defined and failure rates of the components involved are known, the optimum number of redundant PCS' can be determined.

7.2.6.1.3 Power Generation Capability of a PCS

A unique characteristic of a Brayton power conversion loop is the ability to vary its power output over a substantial range by regulating the pressure level of the working gas. If this capability were utilized in the reactor power module it would have both positive and negative effects on system nuclear safety.

A PCS designed to generate greater-than nominal power in an emergency will have a waste heat rejection radiator area much larger than that needed for nominal power. Consequently such a system (operated at nominal power output) will have low compressor inlet temperatures and high system efficiencies with attendant safety advantages due to the lower reactor thermal power generation rate. The additional safety advantage would be the ability to utilize excess reactor power resulting from a PCS failure, by adjusting the operating point of the remaining PCS units.

The negative safety aspects of this excess power generation capability include the greater collision and replacement hazards associated with bigger radiator area, and high reactor power levels during emergency power generation operation. The latter situation occurs when one reactor PM fails and the remaining PM power level is increased to satisfy the full Space Base power demand. Depending on the radiator area, the power output of the operating reactor may have to be more than doubled and the temperature levels in the PM increased by approximately 55^{o}K (100^{o}F). In that case, nuclear radiation levels in the immediate vicinity of the operating PM will be correspondingly higher. The increased temperature levels of the PM also increase the stress on components and thus lower the system safety.

7.2.6.2 Incorporation of a Separable Heat Exchanger

The use of a Separable Heat Exchanger (SEHX) would allow separate replacement of either the reactor shield assembly or the PCS (Brayton power conversion loop and heat rejection loop) so that the logistics of power module replacement and disposal would be simplified. From a nuclear safety viewpoint, however, a SEHX also presents potential safety hazards that require future design and performance studies. The ability to replace only the PCS and thus avoid the premature replacement of the reactor is a definite safety advantage which was discussed previously in Section 7.2.6.1.2. The use of a SEHX also creates performance penalties that effect nuclear safety. For example, inclusion of a "SEHX" increases the temperature differential between reactor and the PCS and, hence, an increase in the reactor outlet temperature and reactor thermal power. By necessity a "SEHX" will be either very large, if radiation is t he heat transfer mode utilized, or compact and complex with many

closely spaced, interlocking fins, if liquid metal conduction is the heat transfer mode. In either case, the act of joining or separating the two halves of the power system at the SEHX will be exacting with a probability for damage and puncture of the SEHX and the intermediate loops. Future design iterations should carefully consider this potential problem.

Utilization of a SEHX would prevent fission products and/or activated coolant, that might leak into the intermediate loop from the primary loop, from reaching the Brayton power conversion loop. Thus, radiation levels in the lower regions of the PCS, where maintenance operations would be performed, could be kept at predictable design levels. However, an ordinary heat exchanger placed in the intermediate loop would provide the same "barrier" function without the replacement hazardds. The latter heat exchanger could develop an internal leak and allow activated material to reach the PCS module, but the probability of two heat exchangers in series failing could be sufficiently low to make it a preferred configuration.

The predominant argument for utilization of a SEHX is the safety advantages it provides for reactor disposal Its use permits disposal by the Shuttle, decreases payload capability required of the disposal vehicle and could increase the orbital decay life of a disposed system by almost a factor of nine (9).

7.2.6.3 Single vs Multiple Reactor Primary and Intermediate Loops

The main safety argument for the use of multiple reactor primary and intermediate loops has been discussed in the previous sections; it significantly reduces the probability of the power module replacement for reasons other than reactor failure. In the reference ZrH power module design, any breach, rupture, or leakage of the reactor primary or intermediate loops, exclusive of internal leakage in the connecting heat exchanger, necessitates the shutdown and replacement of the power module. Such an accident would not require power module replacement if an alternate set of primary and intermediate loops were available. The potential nuclear hazards for PM shutdown, replacement and disposal would be eliminated even though the hazards due to released fission products and activated coolant would still exist.

Multiple primary and intermediate loops would also lessen radiation levels at the PCS in the event an internal leak developed in the primary-to-intermediate loop heat exchanger. A switch to the alternate loops would prevent continued leakage of activated material into the Brayton loop heat exchangers. The radiation levels in PCS would decrease with time as the activated material trapped in the failed circuit gradually decayed in activity.

The safety disadvantage of multiple primary and intermediate loops lies in the additional components, isolation valves, and the more complex control system and Brayton loop heat exchanger designs required. System piping and control could become extremely complicated if multiple primary and intermediate loops were combined with multiple operating PCS' and multiple redundant PCS'.

7.2.6.4 Brayton Power Conversion System Location

A power conversion system in a space reactor power module is usually located as close as possible to the reactor to limit heat losses and pumping power requirements in the reactor primary or intermediate loop. In such a close coupled configuration the PCS can be placed on the near side between the reactor and Space Base, or on the far side of the reactor where it is inaccessible from the Space Base. Another alternate is to neglect the performance advantages of the close coupled locations and separate the PCS from the reactor so that it can be easily reached for maintenance and repair. This latter objective can be attained by placing the PCS at the rear of the Power Module near the Space Base boom junction.

Major safety differences do not exist between the locations mentioned, but the separated arrangement offers some advantages. For a given shield design, maintenance and repair operations on the PCS would be performed in a lower radiation level environment with the separated arrangement. However, a close coupled configuration could have the same radiation dose rate levels at the expense of a slightly heavier shield.

The effect of radiation dose rate as a function of distance for repair and maintenance is discussed in Section 7.3.3 of this volume.

The ease of access, repair and parts replacement increases the reliability and life of the PCS at the separated location, thus increasing its safety. In addition, the PCS could be located inside a thermally-insulated "engine room" enclosure having an air lock access to the Space Base, which would provide greater physical safety for the maintenance crew. An engine room facility could also be made available for the close coupled configuration with the addition of a longer access tunnel between the Space Base and the PCS location.

The safety disadvantage of the separated configuration is the long intermediate loop length needed to transport the reactor heat to t he PCS. The loop is more exposed to accidental physical damage than a similar loop in a close coupled configuration and increases reactor outlet temperature. Increased piping insulation can resolve the latter problem.

The close coupled configuration with the PCS outboard of the reactor has no safety advantage but has a disadvantage because of its inaccessibility for maintenance and repair.

CONCLUSIONS

1. Multiple PCS operation per reactor is the preferred configuration to enhance nuclear safety, providing reduced probability of reactor over-temperature due to abrupt loss of cooling accident.

2. Multiple reactor primary and intermediate loops enhance nuclear safety; they provide for isolation of potential NaK leaks, can reduce reactor replacement frequency and provide means for emergency reactor cooling.

3. A separable heat exchanger can significantly improve the reactor disposal phase of the mission; it increases orbital lifetimes, allows for replacement of the reactor-shield instead of the entire PM and decreases the overall disposal payload.

4. Increased separation distance between the PCS and reactor provides more flexibilility for PCS maintenance and repair (lower radiation dose rates) and decreased shield weight.

7.3 SPACE BASE NUCLEAR SAFETY OPERATIONS STUDIES

The following discussions provide additional data and more specific information on four areas of nuclear safety operations:

1. On-Board Radiological Safety Program

   The program and equipment implemented on board a Space Base for the protection of the crew and equipment.

2. Isotope Handling Considerations

   Design and operational considerations involved with the safe handling of tracers and isotope capsules.

3. Reactor Maintenance and Repair

   An analysis of the safety considerations involved with reactor power module repair and maintenance.

4. Reactor Disposal Techniques

   An analysis of the safety aspects of various reactor power module disposal techniques.

7.3.1 ON-BOARD RADIOLOGICAL SAFETY PROGRAM

The primary purpose of the on-board Radiological Safety Program is to provide the equipment and personnel required to protect the crew from radiological hazards associated with the program. This can be accomplished by a combination of continuous monitoring of the crew status and hazardous areas, coupled with appropriate alarms for radiological emergencies. The data acquired in assuring the protection of the crew will be equally valuable in establishing subsystem exposure and experiment interference effects associated with the radiation environments.

It should be noted that the Radiological Safety Program is required even if the Space Base did not employ nuclear reactors for electric power, since the natural environment itself is a significant source of radiation.

Knowledge of the status of the crew's radiation exposure and dose rate at which the exposure takes place, is important for the following reasons:

1. Assurance that individual crew members can perform adequately will be influenced by the prediction and detection of early and progressive responses to radiation exposure.

2. Records of accumulated dose are necessary in establishing career radiation limits.

3. Response to emergency radiation conditions must be based on accurate knowledge of exposure and exposure rate.

The equipment required to provide this data must be sensitive to a wide spectrum of particles and energies due to the natural, reactor induced, and isotope inventory radiation environments. Absorbed dose and relative biological effectiveness must be determined at both skin and critical organ depths. Since no one type of equipment can meet these criteria, a Radiological Safety Program will have to incorporate a variety of equipment and procedures. The combined program, illustrated in Figure 7-2, can be discussed in terms of the following requirements.

1. Passive Dosimetry System

2. Active Dosimetry System

3. Health Physics Instrumentation

4. Biological Dosimetry System

5. Personnel Requirements

The passive dosimetry system would consist of small packets to be worn by each member of of the crew to record his individual absorbed dose. The active dosimetry system would consist of dose rate monitors placed at key locations. This system would provide useful information needed to calculate biological exposures from the absorbed doses. It should also be connected to an alarm system to provide dose rate information during a radiation emergency. The Health Physics instruments would consist of various detectors necessary to monitor the man y different types of radiations and to calculate the biological exposures to the crew from these radiations. The biological dosimetry system would consist of tests the medical staff can perform to verify the physical dose measurements on individual crew members.

7.3.1.1 Passive Dosimetry System

The objective of the passive dosimetry system is to provide a measure of the accumulated abosrbed dose of each individual crewman. Since the system must be continuously in the possession of the crewman, it must be small, light and must not interfere with the performance of his regular duties.

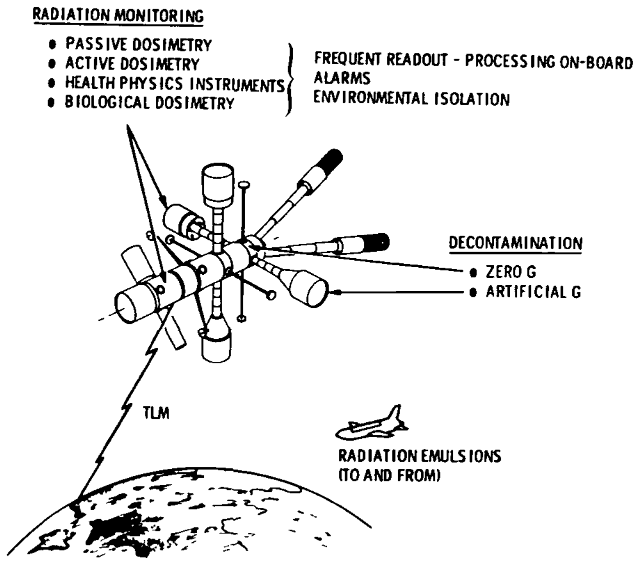


Figure 7-2. Radiological Program

The passive dosimetry system would consist of small packets of nuclear emulsion film and thermoluminescent powder or rods. Each crewman should have one or more of these packets which he is responsible for wearing at all times. During the initial flights, the crew may be asked to wear up to four packets (head, chest, back, thigh); however, past experience at nuclear facilities shows the more complicated the dosimetry system, the less likely that all dosimeters are worn. Later flights may rely on one, or possibly two passive dosimeters for each member of the crew.

The Radiation Safety Officer (RSO) should have the equipment to periodically read and record the passive dosimeters. One important drawback of this type of system is that it is an "after the fact" monitor. Since there may be a need for a decision based on up-to-date crew exposure records the passive dosimeters should be read and recorded frequently. A reasonable system would require that each crewman have a Thermal Luminescent Dosimeter (TLD) rod connected with an identification card. This card would be inserted daily into a special reader connected to the data management system. The data management system would then give a daily readout (capable of monitoring in the Base and by ground systems) of the individual's absorbed dose, the quality factors as obtained from the active and Health Physics systems and the resultant biological dose.

A second reason for frequent evaluation of the passive dosimetry system is to prevent repetition of high exposures. Situations, such as misuse of the x-ray unauthorized entry in radiation areas, and localized radiation streaming due to micrometeorite damage to the reactor shield, may be detected by an investigation of a higher than normal exposure reading. Frequent checks can thus prevent exposure from faulty procedures or changed radiation conditions.

In addition to evaluation by the on-board Radiation Safety Officer, the passive dosimeters can be returned to Earth for more detailed evaluation. Film emulsions, in particular, require specialized development and reading techniques to obtain maximum information. Arrangements would have to be made to tranpsort shielded film to and from the base for periodic changes. The passive dosimetry system can also make use of photoluminescent glass, plastic polymers or or foils. Multiple systems with more than one dosimeter should be considered.

7.3.1.2 Active Dosimetry System

The active dosimetry system must have two primary functions. First, it must provide additional data that can be used to evaluate the biological exposure of each crew member. In particular, this information would include a time profile of the dose and a depth dose distribution. Second, the system must provide warnings and alarms during a radiation emergency.

The active dosimetry would consist of several sets of tissue equivalent ion chambers located throughout a Space Base. These ion chambers shielded with 0.7 mm and 5.0 cm of a tissue equivalent material would provide a reading of both integrated dose and dose rate at tissue depths approximating the skin and the critical organs.

Ion chambers associated with the active dosimetry system require the following characteristics:

1. High sensitivity - To cover a wide range of dose rate
2. Good response time - Must be able to follow contracted dose rate
3. Tissue equivalency - Behaves according to Bragg-Grey criteria (Reference 7-2)

4. Capable of integration with data management and alarm systems

5. Easily read and interpreted by the crew

6. Low drift rate

7. Minimum maintenance, calibration, power and volume requirements

8. Emergency power through back-up power supply system

The location of the ion chambers must be selected based on both primary functions. The first set should be placed "outside" the Space Base. This set would be used to predict radiation exposure during any extravehicular activities. It would also be used to evaluate external radiation conditions particularly during a solar flare. The second, third, and fourth sets should be placed in the Space Base, one at the reactor end, one in the center and one near the far end. The remaining sets of ionization chambers could be placed throughout the Base in high occupancy areas or near experiments sensitive to radiation levels. Through the data from the active dosimetry system, and from the Health Physics measurements, the RSO can determine a quality factor to apply to the crews absorbed dose to determine biological dose. Depending on time limitation and special circumstances, this quality factor can be an average figure applied to all crew members or a specific number applied to one specially investigated case.

The readout from the ion chambers should be connected to remote readouts at the reactor console and/or the RSO's work station. The output should also be connected to an alarm system. The system would alert the captain and crew of impending radiation emergencies. A typical alarm system would have three levels. The first, set at 0.1 rad/hr would "alert" the operating crew of high radiation levels. The second level, set at 1.0 rad/hr, would "alarm" the crew to prepare for emergency action. The third level, set at 10.0 rad/hr would alarm the Base that emergency action is required. Specific preplanned emergency plans would then be put into effect at each of these levels.

The RSO would be responsible for the maintenance, calibration and evaluation of the ion chamber monitoring system. He must, therefore, have the spare parts, the calibration sources, and the time scheduled, to maintain the system.

7.3.1.3 Health Physics Instrumentation

The third radiation monitoring system comes under the heading of Health Physics instruments. These equipment, also under the care of the Radiation Safety Officer, would have two prime functions. The first is to provide radiation safety data similar to the data required around any nuclear facility. Radioisotope heat sources must be monitored for leakage, x-ray machines and radioisotopes must be periodically surveyed and work near the reactor would require surveys of the radiation levels. Thus the Radiation Safety Officer would require a full complement of air monitors, survey instruments, contamination meters, and other Health Physics equipment. At the present time there is a large selection of instruments on the market. However, few instruments have been flight tested and meet the necessary requirements of weight, volume, shielding, and low maintenance. Prior to launch of a Space Base a development program is needed to assure that required Health Physics instruments are qualified for flight and will give meaningful data in the radiation fields encountered during flight.

The second main function of the Health Physics instruments is to provide the Radiation Safety Officer with sufficient data to assign a realistic quality factor to the absorbed dose readings from the passive dosimetry system. These instruments would include protron spectrometers, neutron detectors, linear energy transfer monitors, depth dose chambers and heavy particle monitors. The need for this sophisticated equipment will depend, to a large extent, on the scope of the experimental program in space radiation prior to implementation of a Space Base. An extensive experimental program could supply the RSO with sufficient data to calculate the biological exposure from the absorbed dose in most situations.

Several of the Health Physics monitors should be connected to alarm and control systems. The air monitors around the reactors and around the isotope capsules (e.g., heat sources) would alert the operating crew of high levels of radioactive contamination. These monitors

could also be programmed to close doors, isolate air systems and circulate air through absolute filters. Contamination monitors in laboratories using tracers can alert the staff of spills that could ruin an experiment or cause a contamination hazard. The radiation monitors and neutron detectors near the reactor should also be alarmed.

7.3.1.4 Biological Dosimetry

The final radiation monitoring system, biological monitoring, provides what may be the best assessment of the severity of radiation damage to an individual. This system would consist of tests to be performed by the Medical staff that would either verify or modify dose estimations made by physical measurements. Many important decisions effecting the mission and the crew members would be based on exposure data. The prime purpose of the biological tests would be to provide data on the effected individual's biological damage to assist in making these decisions. Biological monitoring is not planned as a day to day monitoring system or a low dose detector. It should be used to evaluate the consequences of high exposure or during emergency conditions.

Although there are many indicators to be measured, hematological changes are the most sensitive indicator. Special difficulties are encountered evaluating the effects from fractionation of the dose, nonuniformity (partial body exposure), quality of radiation, and other stresses (weightlessness, etc.). However, in spite of these difficulties, the hematological changes, combined with the physical measurements, will give a good indication of the severity of the radiation damage from an exposure to space radiation.

In addition to blood counts, the medical staff can also use other clinical signs to determine the magnitude of an exposure. Reduced resistance to stress, tendency to fatigue, low grade infection, and decreased blood oxygen transport are all signs of chronic radiation exposure. Erythema can be used to measure high level skin exposures and chromosome changes can be observed after radiation exposures. As with the passive dosimetry system, blood samples, urine samples for determining internal contamination, and other biological samples can be returned to earth for detailed evaluation.

7.3.1.5 Personnel Requirements

Manning of the Radiological Safety Program will be an important consideration when determining the makeup of the crew. With respect to radiation safety the crew may be divided up into four groups. Those groups would include the Radiation Safety, Medical and Operations Staffs, and the remainder of the crew. It should be noted that, with the exceptionof the Radiation Safety Officer, the radiation safety duties of these personnel would be on a part-time basis. Full-time participation would be required only during emergency situations. For example, radiation safety technicians could be drawn from the crew members normally engaged in instrumentation and electronic maintenance and repair. However, in planning crew staffing, it should be recognized that a portion of these technicians' time would be devoted to the Radiological Safety Program and that special, preflight training is required for these individuals. In addition, the requirement for a radiological safety program does not result solely from the use of nuclear, electric power generation systems (e.g., reactor power modules). The natural radiation environment, the uncertainties in the environment (e.g., solar flares) and the use of isotope sources in the experiment program engender potential hazards which require the implementation of a radiological safety program. For example, in a Base with a complement of 50-60 crewmen, it has been estimated that the use of nuclear reactors would result in an additional man being occupied half-time in the Radiological Safety Program out of a maximum of effectively three men devoting full-time to the Program.

The Radiation Safety Staff should conisist of the RSO and two or three assistants. The radiation safety duties of these people would be part time responsibilities and they should be available for part-time duties with the Medical, Reactor Operations, or Experimental Staffs. For two reasons it is preferable to have several part-time people responsible for radiation safety rather than one full-time. First, the radiation safety work will usually be routine and morale will improve with the assignment of other tasks. Second, in a radiation emergency more than one man will be needed to provide the required radiation safety coverage.

The background of the RSO should include education in radiation biology and instrumentation. His training and job experience should include considerable Health Physics work. As RSO, his major responsibilities are to care for and interpret the active and passive dosimetry systems, and the Health Physics instruments, and to advise on matters concerning radiation safety and radiation emergencies. His routine work would include (1) daily checks on the monitoring

system, personnel exposure calculations and records; (2) Health Physics coverage and surveys; (3) supervising the Radiation Safety technicians. His emergency duties would include dose prediction and dose determination, radiation control, and contamination control.

The Radiation Safety Technicians should have experience working in and around nuclear facilities. They also should be knowledgeable of the radiation safety instrumentation, and procedures, the responsibilities of routine Health Physics surveys, policing passive dosimetry requirements, data management inputs and data taking. Their emergency responsibilities would include Health Physics surveys and monitoring work in high radiation areas.

The Medical Staff will have two radiological safety responsibilities. The first is to provide dose information for biological monitoring records. The second is to provide medical services for overexposed crewmen. The Medical Staff must, therefore, have training and experience in working with radiation sickness accidents.

The Radiological Operations crew will be responsible for reactor operation, work around the reactors and isotope heat sources, and emergency work involving radiation exposure. For this reason all the members of the operating crew should have attended a training program in radiological safety, and should be able to evaluate radiation risks and to interpret the radiation safety monitoring system. A second impact on this crew involves their availability in a radiation emergency. In order not to exceed mission dose levels, crew members with a high accumulated dose would not be available for emergency work. Crew rotation schedules and work assignments will be dependent on total exposure to the individual members of the crew. Key positions may have to be rotated at some fraction of the mission exposure level to assure their availability in an emergency.

The remainder of the Space Base staff needs only sufficient radiation safety knowledge to allow them to make valid risk judgments and to function effectively in a radiation emergency. Prelaunch and on-the-job training courses can provide this knowledge.

Table 7-12 presents a representative breakdown of personnel requirements, indicating duties and background training required.

7.3.1.6 Equipment Requirements

Table 7-13 indicates representative equipments required for a Space Base Radiological Safety Program. The equipment quantities indicated are based on a nominal 50-man crew. Requirements for additional personnel can be approximated by linear scale-up.

7.3.1.6.1 Passive Dosimetry Equipment

The passive dosimetry equipment has been grouped under TLD (Thermoluminescent dosimeters), which are read and interpreted on the Space Base, and film which would be returned to earth for analysis. The integrated TLD reader/data management system must be developed, and at present no reader equipment has been flight tested. The film badges are expected to be similar to those used on the Apollo Program.

Location of the TLD readers should be selected for convenience of access to insure daily readout. A minimum of two locations have been noted in the Table 7-13. However, it may be more realistic to provide reader stations in each of the living quarter areas.

7.3.1.6.2 Active Dosimetry Equipment

This system consists of the tissue equivalent ion chambers and associated interface equipment. Since this system is part of the radiation monitoring and alarm system, readouts must be provided at key decision and interpretation areas, i.e., Command console and the Radiation Safety Office. It is expected that the sensors employed in the system would be similar to the Van Allen Belt dosimeter used on Apollo missions.

7.3.1.6.3 Health Physics Equipment

The Health Physics equipment described in Table 7-13 provides monitoring of radiation conditions within the Space Base and assists the RSO in establishing quality factors for the measured absorbed dose (quality monitors). In general, the instruments cited have not been

Table 7-12. Personnel Requirements for Radiological Safety Program

Personnel Type	Duties	Remarks
Radiation Safety Officer	• Care for radiation monitoring equipment • Keep records on accumulated exposure • Make surveys, interpret data from radiation monitors • Emergency responsibilities/decisions • Radiation safety training program • Supervision of Radiation Safety Technicians • Collate Data Management information from Base and Ground Links	• One individual • Training - Health Physics certification, Radiation Biology, Instrumentation • Part-time responsibilities, also active in scientific experimentation
Radiation Safety Technicians	• Instrument maintenance, repair and logistics support • Health Physics surveys • Emergency responsibilities • Read and record TLD, film, and police passive monitoring regulations	• Two individuals • Training - Nuclear facilities work - Instrumentation and Health Physics operation and maintenance experience
Medical Staff	• Responsible for biological dosimetry • Care for overexposed	• Training and experience in treating radiation sickness
Radiological Operations Crew	• Emergency responsibilities • Reactor repair, EVA's other non-routine jobs involving radiation exposure • Assist RSO as required	• At least six, individuals with nuclear facility experience • 40-hour (minimum) preflight radiation safety training program at National Laboratory • In-flight training by RSO
Remainder	• Emergency responsibilities • Work amongst radiation hazards	• 6-hour (minimum) radiation safety training program by RSO or comparable individuals. • In-flight training by RSO

NOTES

1 A maximum of 3 crew members would be devoted full-time to the radiological safety program, during a period of normal operation.

2. The use of nuclear reactors for electrical power generation accounts for approximately one man, half-time, of the crew utilization estimate in Note 1.

Table 7-13. Radiological Safety Program Equipment (50-Man Crew)

System Description	Equipment Required	Responsible Individuals	Remarks
1.0 PASSIVE DOSIMETRY			
A. TLD (Thermoluminescent Dosimeters)	50 TLD rods and identification medium	Crew - wear at all times and read once per day	Readers and data management system interfaces require development
	A minimum of two TLD readers connected to data management system	RSO - for interpreting and maintaining readers. Radiation safety technicians	Possible interaction with ground support
	TLD reader in RSO office 200 TLD rods for backup and emergency distribution	RSO - for emergency and backup data	Chest, thigh, head and back rods may be required to evaluate unusual conditions
B. Film (Nuclear Emulsion)	50 film badges	Crew - to wear at all times	Badges will be change monthly - Ground readout
	50 spare badges	RSO - for backup data	Ground support will read, evaluate and notify RSO
	Shielded shipping container		
2.0 ACTIVE DOSIMETRY	2 ion chambers at 8 locations (16 ion chambers)	RSO - maintenance and repair, radiation safety technicians	One shielded with 0.7 mm and one with 5 cm of tissue equivalent material Range: 0.01 to 100 rad/hr
	Associated electronics and data management interface for 8 stations	Operations crew	Possible ground support back-up.
	Readout equipment at RSO office and command and reactor consoles.	Operations crew	Possible ground support back-up
	Alarm system and interface equipment	Crew - knowledge of expected response to alarm Radiation safety technicians	Three alarm levels 0.1, 1.0, 10 rad/hr. First two alert RSO and command console. Last alerts base
3.0 HEALTH PHYSICS			
A. Air Monitors	Alpha particle air monitors with scintillation crystal	RSO - maintenance, repair and data interpretation Radiation safety technicians	Isotope capsule monitoring, e.g. Pu-238, Cm-244
	Beta-Gamma air monitors		Contamination monitor
	Portable air samplers		Contamination detection and follow-up
B. Contamination Monitors	Proportional counters	RSO - maintenance, repair and data interpretation Radiation safety technicians	To count smears and air samples
	Portable Alpha contamination survey meters		Contamination detection and follow-up
	Portable beta-gamma contaminants survey meters		Contamination detection and follow-up
	Low level beta monitors		May be required for C-14 or tritium work
C. Radiation Monitors	Hand held radiation survey meters	RSO - maintenance and data interpretation Radiation safety technicians	Similar to Apollo radiation survey meter
	Neutron, rem responding, portable survey meters		
	Low energy gamma survey meters		
	Personnel dosimeters		Similar to Apollo radiation dosimeter
D. Quality Monitors	Depth dose tissue equivalent ion chambers	RSO - maintenance, repair and data interpretation	Identical to active dosimetry system
	Proton detectors		Similar to Apollo nuclear particle detector system
E. Non-ionizing Radiation Monitors	Microwave detectors	RSO - maintenance, repair and data interpretation Radiation safety technicians	Sensitivity: 0.1 mw/cm^2 to 100 mw/cm^2
	Laser power level meters		Sensitivity: 0.1 joules/cm^2

developed for space application, with the exception of applicable Apollo hardware. This lack of development applies not only to flight qualification requirements but also operability in the presence of the Space Base radiation background. Development of the required instruments should stress ease of maintenance and versatility (incorporate several functions in one piece of hardware).

Air monitors are required, particularly in laboratories where isotope capsules or isotope tracers are in use. These monitors must be capable of detecting 1/10 MPC (maximum permissible concentration - see Appendix A, Section A.5 for MPC of typical isotopes), of the isotopes to be detected. These monitors would be connected to alarms, both in the area being monitored and in the Radiation Safety Office. In order to detect low concentrations, the air monitor must be shielded from the background radiation.

The proportional counter is used to quantitatively measure, the degree of contamination. The sensitivity of the device will depend primarily on the shielding that can be provided against the background radiation. The hand held radiation survey meters should have a sensitivity ranging from 18 mrad/hr to 100 rad/hr. Equipment in the Radiation Safety Office must include a selection of radiation sources for calibration of the various instruments and meters. All portable radiological monitoring equipment should be designed to be operable outside of the Space Base, so as to be applicable to EVA surveys.

In addition to instruments required to monitor ionizing radiation, equipment must also be provided to monitor leakage in microwave generators and laser equipment used in experiment laboratories. The sensitivity indicated for a microwave detector is based on the present exposure standard of 10 mv/cm^2; however, the trend is currently toward lower allowable exposures. Similarly, the sensitivity indicated for a laser detector is the threshold of value for damage to the retina of the eye.

7.3.2 ISOTOPE HANDLING

The isotope sources which may be on-board, internal to the Space Base, include "closed" isotope sources and "open" isotope sources. Closed sources refer to sealed capsules in

in which the isotope is totally contained, such as capsules which may be incorporated in waste management systems or used to insure temperature control of equipment. The "open" systems include isotopes such as tracer materials that may be employed in such a manner, that the isotope is "free" within the environment of the Space Base although contained within the specimen being tested. Isotope sources may pose a hazard not only from external exposure from direct radiation but also internal exposure from ingestion of radioactive material, should the isotope be released indescriminately to the environment.

7.3.2.1 Closed Isotope Sources

The implementation of closed sources on the Space Base, involves considerations related to both the safety of the general populace and on-board the Space Vehicle. Representative AEC guidelines for current capsule design for space application are shown in Table 7-14 and apply primarily to protecting the earth's general populace. These guidelines have been derived for the Multihundred Watt Thermoelectric Generator program and further amplification may be found in References 7-3 and 7-4.

On board the spacecraft several general guidelines as to location and protection for isotope capsules has been noted in Section 6.3.1.4. Specifically, shielding against radiation and thermal hazards have been noted. The extent of these requirements depends primarily on the quantity and type of isotope used on-board. Areas that contain isotope should be clearly identified by visual labeling, noting the type of radiation being emitted and the level of the radiation (dose rate). Should sufficient quantities be involved, the amount of time which personnel can spend in the area should also be noted.

Although sealed sources generally preclude the release of the contained isotope, some isotopes produce gas as a by-product of the radioactive decay process (e.g., Pu-238 and Cm-244 release helium as a by-product of alpha-decay). When such capsules are to be used for a long period of time, venting of the capsule may be required to preclude eventual rupture of the capsule. When venting is provided, the release of radioactive gases also associated with the decay process (e.g., radon and radon daughters in the case of Pu-238) should be precluded from release to the in-board environment.

Table 7-14. Isotope Capsule Safety Design Guidelines

GROUND HANDLING AND TRANSPORTATION

- The heat source shall be designed to
  - a Preclude inadvertent release of or contact with the fuel during all ground handling operations Ground handling procedures shall be compatible with radiation exposure limits set forth in AEC-MC-0524
  - b Preclude the accumulation of radon and radon daughters in excess of the values set forth in AEC-MC-0524, especially in vented systems
  - c Minimize heat source degradation from handling, aging, and/or storage by proper manufacturing and scheduling of factory-to-flight processes and operations
- For shipping and handling the RTG or heat source, the shipping container must satisfy the requirements of the AEC as set forth in AEC-MC-0529 and the Department of Transportation (DOT), as applicable, for any potential shipping modes

PRELAUNCH AND LAUNCH

- The heat source shall be designed to
  - a Immobilize the fuel during all potential prelaunch and launch failures Sequential environments (e g , overpressure and impulse, fireball, shrapnel, impact, after-fire, and adverse thermochemical or chemical reactions) consistent with the launch vehicle shall be considered
  - b Minimize ground contamination of the launch site
  - c Satisfy the above prelaunch and launch requirements for at least one month following a launch pad abort to facilitate recovery and return of the fuel to radiological control

ASCENT

- The heat source shall be designed to immobilize the fuel
  - a And preclude biospheric contamination under all ascent abort failures including those sequential events cited in (a) under Prelaunch and Launch
  - b During and after credible sequential reentry and terminal velocity impact situations
  - c In order to facilitate fuel recovery following land impact for a period of at least one year
  - d In order to facilitate fuel recovery from water depths up to 600 feet for a period of at least one year

ORBITAL AND SUPERORBITAL

- The heat source shall be designed to immobilize the fuel
  - a And preclude release of fuel in space as a result of mechanical, chemical and/or thermal degradation
  - b During and after credible sequential reentry and terminal velocity impact situations
  - c In the event the RTG or the heat source is recovered from space
  - d In order to facilitate fuel recovery following land impact for a period of at least one year
  - e In order to facilitate fuel recovery from water depths up to 600 feet for a period of at least one year

OTHER CONSIDERATIONS

- Long-term fuel immobilization under conditions of earth burial is desired
- AEC-MC-0524 specifies radiation exposure criteria applicable to all phases of the RTG program
- Subcriticality of the heat source under all normal and accident conditions shall be assured

The Health Physics equipments described in Section 7.3.1.6 would be used to monitor the performance and condition of the sources and areas containing the sources.

7.3.2.2 Open Isotope Sources

The hazards involved with the use of open isotope sources (tracers) depends on the type of isotope and quantity to be brought on the Space Base. These sources are expected to be stored in very small quantities, so that the hazard is mainly from ingestion in the event of an inadvertent release, rather than from direct radiation.

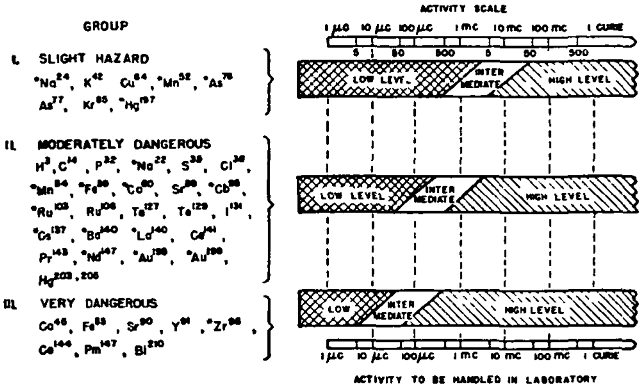
Table 7-15 presents a general guide as to the relative hazard associated with handling quantities of the various isotopes. The eventual determination of the degree of protection required will depend on the specific isotopes used, the allowable MPC (maximum permissible concentration) associated with these isotopes, and the specific quantities that could be released during a "spill" (see Appendix A for MPC for particular isotopes). The MPC must be considered on the basis of 168-hour week (continuous exposure for the crew on the Space Base. By considering the total volume which could be contaminated and the quantity of the specific isotope required to be stored on board, the degree of contamination in terms of MPC level could be determined. The following approach to establishing handling and equipment requirements is considered to be representative. The fractions and multiple of MPC's is considered realistic but is used here strictly for discussion. Table 7-16 illustrates the progressive requirements.

7.3.2.3 Decontamination Techniques

In the event of leakage of isotope from a capsule or a spill of tracer elements in the experiment laboratories, techniques would have to be implemented to return the affected areas to normal use. In addition, personnel returning from EVA, or reactor maintenance may carry deposits of radioactive material (NaK, fission products), and would have to be decontaminated prior to being allowed general access to the Space Base.

Table 7-15. Hazard from Absorption into the Body

Selected radioisotopes grouped according to relative radiotoxicity with the amounts considered as low, intermediate or high level, in laboratory practice



NOTES

Effective radiotoxicity is obtained from a weighting of the following factors

- Half-life
- Energy and character of radiations
- Degree of selective localization in the body
- Rates of elimination
- Quantities involved and modes of handling in typical experiments

The slant boundaries between levels indicate border line zones, and emphasize that there is no sharp transition between the levels and the associated protection techniques.

The principal gamma-emitters are indicated by asterisk (e g, $^*Na^{24}$) The above level system does not apply to the hazards of external irradiation

Table 7-16. Requirements for Open Isotope Source Handling

Degree of Possible Contamination	Open System Handling Requirements
0 1 MPC	Isotope may be used in the open Atmosphere control for the area should be fitted with absolute filters to minimize dispersion
1.0 MPC	Isotope should be stored and used only in a glove box. The glove box should be maintained at a pressure lower than ambient The air exhaust from the glove box should be fitted with an absolute filter to trap particulate matter The air intake should also be fitted with an absolute filter to preclude dispersion in the event of a pressure reversal.
10.0 MPC	The isotope should be stored and used in in an access controlled laboratory Access to the laboratory should be through an airlock. Handling procedures in this lab would include the glove box precautions shown above A separate atmosphere control and water supply should be provided for the laboratory. The laboratory should provide for protective clothing, decontamination equipment personnel without further contamination of the overall vehicle

In practice, laboratories, where contamination can be anticipated, incorporate equipment to minimize the effects of contamination (see Paragraph 7.3.2.2) and also design surfaces (walls, floors, work tables, etc.) to minimize porosity and facilitate decontamination (Reference 7-5). Conventional decontamination techniques include vacuuming, washing (wiping) with absorbent wipes, paint stripping and refinishing to remove contamination as well as over-painting to prevent further spreading once lowest achievable levels are reached. Clearly the general application of these techniques would not be applicable to zero "g" areas of the Space Base, since without a gravity field a large percentage of the contaminated material could be in suspension. Vacuuming appears to present the promising approach to initial decontamination. In severe cases this could be carried to the extent of depressurizing the entire compartment affected (accompanied by an air flush) through an absolute filter.

However, considerable innovation and development of techniques would be required to deal with residual radiation in zero "g". It might appear that restricting, isotope handling to artificial "g" areas would relegate the problem of decontamination to conventional means. However, the hazard involved with a loss of artificial "g" capability, could cause a contamination situation and subsequently require zero "g" decontamination techniques.

A similar problem is encountered in decontaminating astronauts returning from EVA. Access to the Space Base will most certainly be accomplished through the zero "g" portion of the Base and, therefore, will require the development of applicable decontamination techniques.

One approach to this problem which could prove more effective in terms of safety is to provide a separate, detachable, Shuttle retrievable module which could serve as a decontamination

area and laboratory for high isotope concentrations. This configuration would serve the purpose of minimizing contamination of permanent portions of the Space Base, provide the interface for accepting and decontaminating crew returning from EVA, and provide isolation areas where a crew member could be treated prior to return to earth. Areas of this module could be allowed to achieve higher contamination levels than would generally be acceptable in permanent areas of the Space Base. In addition, at some threshold value, the module could be replaced, and returned to earth for conventional decontamination and refurbishment.

7.3.3 REACTOR POWER MODULE MAINTENANCE AND REPAIR

The Space Base Electrical Power System (EPS) was analyzed to determine the nuclear safety considerations associated with the repair and maintenance functions of the Reactor Power Modules. The reference EPS as defined in Section 3.2.2.1 was used as the basis of the evaluation. An "engine room" approach was assumed (Figure 7-3). Operating conditions considered included the case where the Power Module (PM) to be repaired was shutdown and the remaining PM was operating at the emergency power level of 600 kWt.

The PM design does not provide for a pressurized or pressurizable engine room, consequently space ambient conditions have been referenced as the working environment for the analysis.

7.3.3.1 Repair and Maintenance Approach

This study evaluated the nuclear safety hazards associated with PM repair and maintenance, and the operational limitations imposed by safety constraints. The objective was to provide a repair and maintenance capability within the limits imposed by nuclear safety. The critical factors considered in the evaluation were:

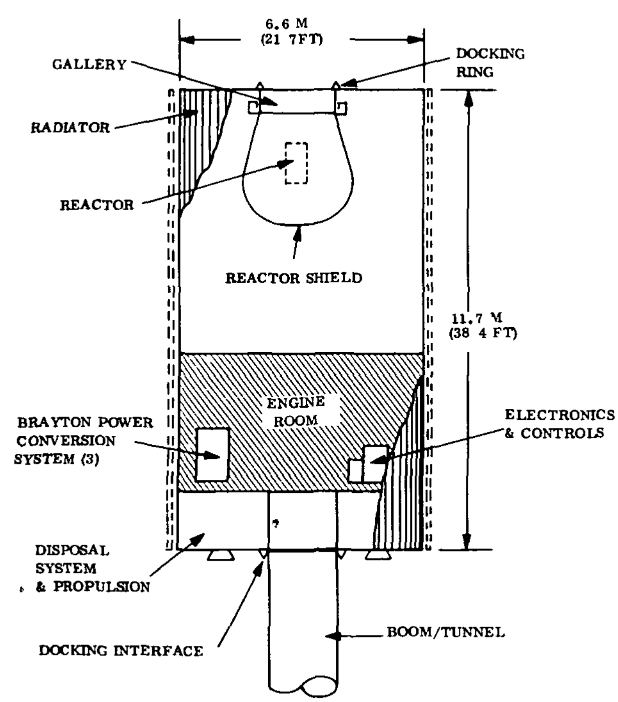


Figure 7-3. Typical Power Module Engine Room Position

1. Working environment (shirtsleeve, EVA, IVA)
2. Temperature constraints
3. Crew stay time
4. Radiation environment
5. Zero "g" constraints

$\Bigg\}$ Objective .... minimize radiation dose to crew

A consideration in each of these factors is that each affect the radiation dose to which an astronaut is exposed, i.e., a pressurized and temperature controlled engine room is preferred because it provides a greater degree of flexibility for the astronaut to effect repairs and maintenance in a minimum of time thereby reducing the integrated radiation dose.

Each of the critical factors was then used to establish the repair and maintenance approach. Four levels of repair and maintenance were considered:

- Piece part
- Modular (black box)
- Component
- Subsystem

The piece part approach was rejected. This approach increases stay times, requires considerable flexibility and dexterity and may also require considerable "trouble shooting", all of which increase total radiation exposure of the repair crew. The modular (black box), component and subsystem approach is recommended since each of these methods can meet the critical factors criteria. For purposes of this study, components are identified as integral units of a subsystem such as a Brayton Rotating Unit or a pump. Subsystems encompass a wider range of the PM and in this case, the most prominent example is a reactor/shield which can be separated from the PM by means of a separable heat exchanger.

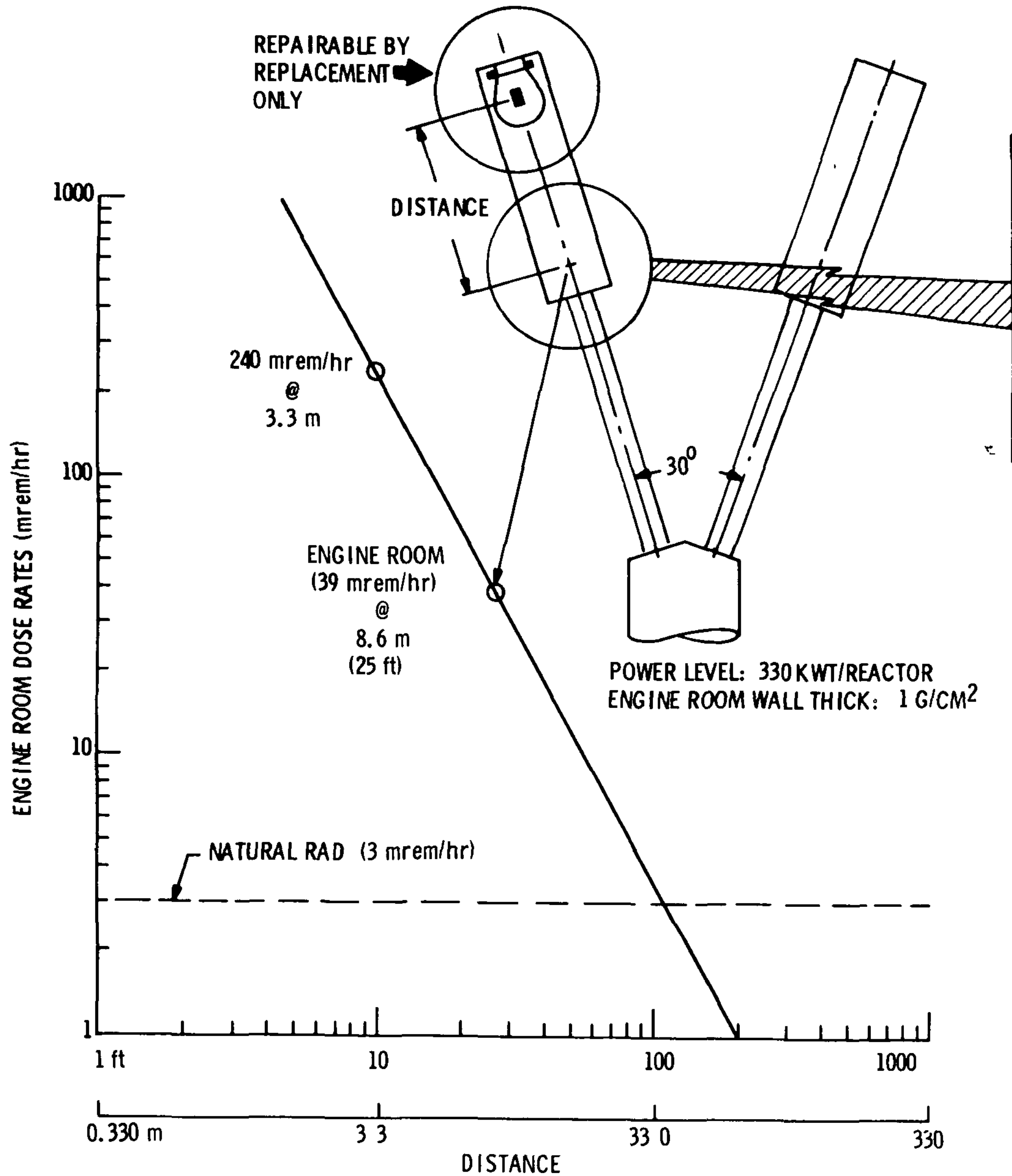
Each of these methods - modular, component and subsystem - represent an approach to repair and maintenance that reduces stay times, facilitates handling and eliminates "trouble shooting" which result in decreasing the amount of radiation an astronaut is exposed to.

7.3.3.2 Radiation Environment

Radiation emanating from both reactors was considered during the analysis. Repair and maintenance within the engine room was based on the conditions that both reactors were operating at the reference power level of 330 kWt each and that the engine room structure provides a radiation shielding effectiveness of 1 gm/cm^2. The nominal distance between the reactor and the engine room is 8.26 m (25 ft) as defined in the MDAC baseline (Reference 7-6). Using this criteria and data from Figure 7-4, the amount of radiation received by an astronaut performing repairs in the engine room is 39 mrem/hr (depth dose). Natural radiation would contribute an additional 3 mrem/hr (depth dose). One can also deduce from Figure 7-4 that repair in the gallery areas (approximately 1.98 m (6 ft) from the reactor) is impractical due to the high radiation levels, in the order of 600 rem/hr. Repairs in the gallery area were also investigated for the case where the reactor to be repaired is shut down and the remaining reactor is operating at the emergency power level of 600 kWt. Data from Figure 7-5 indicates the radiation dose rate in the gallery area is in the range of 200 rem/hr twenty-four hours after shutdown and still relatively high at 0.9 rem/hr ten days after shutdown. Based on these data, it is concluded that repair and maintenance in the reactor and gallery areas would not and should not be performed after the reactor has been operated, due to the excessively high radiation levels.

7.3.3.3 Repair and Maintenance Frequencies

Repair and maintenance frequencies and stay times required to effect repairs were also considered. Repair frequency data presented in Figure 7-4 was obtained from a North American Rockwell (NAR) study (Reference 7-7). These data indicate that as many as 21 repairs will have to be made on the Brayton Power Conversion Systems over the 10-year mission. These figures are based on estimated failure rates and when simplified, result in a repair rate of one per six months per Power Module. The same study also presented data of estimated times required to effect repairs. An average repair time of 1.5 to 2.0 hrs, including transit time along the power module support boom, was derived from these data. Assuming a conservative approach that the entire two hours is spent in the engine room at a distance of 8.26 m (25 ft) from the reactor, the astronaut would then receive an integrated depth dose of 78 mrem (39 mrem/hr from Figure 7-4) from the reactor and approximately



ENGINE ROOM REPAIR FREQUENCY (REF 7-7)

ITEM	REPAIR FREQ/ 10 YEARS
PCM WITHOUT GAS MANAGEMENT	3.0
GAS MANAGEMENT SYSTEM	1.75
HEAT REJECTION LOOP	1.75
PCU CONTROLLERS	1.14
ELECTRICAL CONTROL PACKAGE	5.34
NaK PUMP POWER SUPPLIES	8.41
TOTAL REPAIRS	21.39

- CREW MEMBER EFFECTS REPAIR ONCE EVERY 6 MONTHS ON EACH* POWER MODULE
- AVERAGE STAY TIME 1.5 - 2.0 HOURS

*DOES NOT INCLUDE REPAIRS ON DISPOSAL MODULE

Figure 7-4. Reactor Power Module Maintenance Frequency

6 mrem (depth dose) from natural radiation sources. The maximum allowable one year average daily depth dose rate is 200 mrem (see Section 4). During the normal course of his daily routine aboard the Space Base, an astronaut receives an average of 91 mrem (depth). If we add the repair dose of 78 mrem from the reactor and the 6 mrem from natural sources (due to the two-hour repair) to the 91 mrem, a safety margin of 25 mrem still remains for the one day period. It is, therefore, concluded, that repair and maintenance in the engine room is feasible and can be performed within radiation exposure limits.

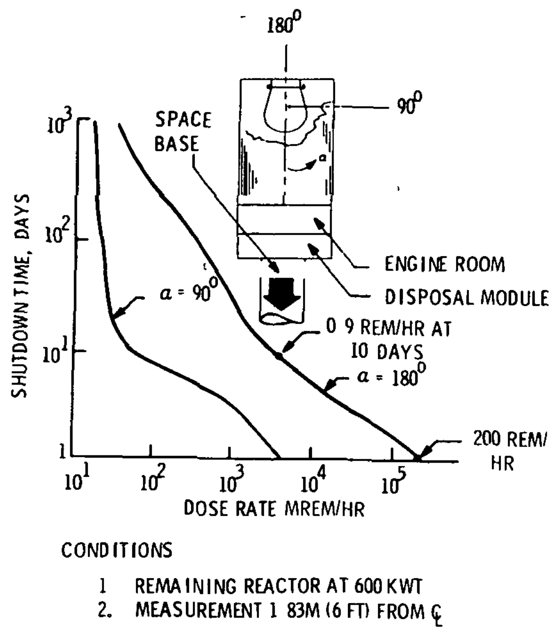


Figure 7-5. Radiation Decay After Shutdown

Longer stay times of up to five hours can probably be accommodated when considering a repair frequency of one per six months.

7.3.3.4 Related Hazards

NaK Piping Repair Hazards - Repair of NaK lines in the primary, intermediate or heat rejection loops is considered impractical in light of the following safety hazards NaK presents:

- Inherent toxicity
- Activation by nuclear radiation
- Potential fire hazard

The reference PM is designed as a single loop system thereby precluding further PM operation should a NaK leak develop. Repair does not appear to be feasible due to the nuclear safety hazards identified above. The hazards are also significantly increased when one accounts for

the zero "g" environment in which the repairs must be made (Reference 7-1, 7-8). However, for future designs, which might include redundant NaK loops thereby providing a means for continued PM operation, a method should be provided for containment of the NaK and safing of the system. One approach to the problem is to incorporate double wall piping or to design the piping insulation for a dual function, i.e., heat insulation and NaK containment.

Rotating Machinery Hazards - Rotating machinery can present a safety hazard to the crew due to potential fragmentation accidents and its dynamic characteristics. Appropriate safeguards should be included in future designs.

Temperature Hazards - High temperature surfaces in the engine room area such as piping, heat exchangers and the PCS should be equipped with protective guards to prevent accidental contact by the crew performing repairs.

Electrical Hazards - Electrical Hazards such as high voltages associated with the PCS should be considered in design of the engine room and protective features incorporated to reduce and/or eliminate them for the protection of crewmen performing repairs.

7.3.3.5 Conclusions and Recommendations

Table 7-17 presents a summary of hazards that have been identified during this study and recommendations to reduce and/or eliminate them. Hazards identified for specific repairs were documented on maintenance and repair sheets (Appendix D), of which Figure 7-6 is a typical example. The principal repair and maintenance guidelines resulting from the evaluation are identified in Table 7-18.

7.3.4 REACTOR DISPOSAL TECHNIQUES

Reactor disposal constitutes one of the prime areas of concern in the use of nuclear reactors for space applications. Terrestrial nuclear safety and handling operations are affected to a greater degree during reactor disposal than during reactor launch ascent and early orbital operations. This is due to the inherent operating characteristics of a nuclear reactor, i.e., the fission product inventory increases as a function of reactor power level and operating time.

Table 7-17. Summary of Typical Repair and Maintenance Hazards

Repair/ Maintenance	Hazard	Recommendation
NaK Lines	• NaK toxicity • NaK Activation • Potential for fire • Reactor radiation • High temperatures	Repairs to NaK lines not recommended Design should consider such features as NaK containment by employment of double wall piping to "safe" the system.
Parasitic Load Resistor	• EVA environment (vacuum, electrical, thermal, radiation hazards	Provide multiple design redundancy
Brayton Control System	• Proximity of NaK coolant • High voltages • Rotating machinery • Proximity of high temperature components • Proximity of high pressure gas management system	• Provide modular (black box) approach to facilitate replacement. • Provide guard rails around high temperature equipment. • Provide protective shields to guard against rotating machinery and electrical hazards. • Sensors and detectors should incorporate redundancy and replacement design philosophy.
Brayton Rotating Unit	All hazards previously noted for engine room area, i.e., NaK toxicity, radiation, temperature rotating machinery, etc.	Design should incorporate quick disconnect devices and mechanical handling features.
Disposal System	• Possible EVA environment (vacuum, electrical, thermal, radiation) • Ordnance • High pressure gas	• Modular replacement • Engine room concept

- SUBSYSTEM/MODULE - BRAYTON POWER CONVERSION LOOP (CONTROL SYSTEM)
- LOCATION - ENGINE ROOM
- ACCESSIBILITY - INTERNAL, THROUGH TUNNEL
- ENVIRONMENT

  TEMPERATURE (°K) - 310 (100°F) (RECOMMENDED)
  RAD DOSE LEVEL - 42 MR/HR TOTAL
  ATMOSPHERE - PRESSURIZED (DESIRED)
  ZERO G
- MAINTENANCE OPERATIONS - REPLACE CONTROL SYSTEM BLACK BOXES AND NaK PUMP POWER SUPPLIES
- REPAIR OPERATIONS - MINOR TROUBLE SHOOTING AND ELECTRICAL CONNECTIONS (PLUG TYPE)
- UNSAFE CONDITIONS
  - EQUIPMENT TEMPERATURES 755°K (900°F)
  - ROTATING MACHINERY
  - HIGH PRESSURE GAS
  - TOXIC NaK
  - ELECTRICAL WIRING
  - RADIATION
- RECOMMENDATIONS
  - PROVIDE ROTATING MACHINERY GUARDS
  - PRESSURIZED, TEMP CONTROLLED AREA
  - BLACK BOX REPLACEMENT
  - SENSORS AND DETECTORS SHOULD INCORPORATE REDUNDANCY AND REPLACEMENT DESIGN PHILOSOPHY

SYSTEMS ANALYSED

- BRAYTON POWER CONVERSION LOOP
- REACTOR PRIMARY LOOP
- INTERMEDIATE LOOP
- CONTROL SYSTEM (REACTOR)
- BRAYTON HEAT REJECTION LOOP
- AUXILLIARY HEAT REDUCTION LOOP
- DISPOSAL MODULE

SUMMARY OF RECOMMENDATIONS

- PRESSURIZED ENGINE ROOM
- TEMP CONTROLLED ENGINE ROOM
- REPAIR OF NaK LINES NOT PRACTICAL
- REPAIR IN GALLERY AREA NOT PRACTICAL

Figure 7-6. EPS Maintenance and Repair Analysis

Table 7-18. Reactor Power Module Maintenance and Repair Guidelines

DESIGN

- Consider use of a pressurized and temperature-controlled engine room
- Consider methods of NaK containment, such as double-walled construction
- Provide modular (black box), component and subsystem level repair capability
- Emergency EVA and IVA suits should be located in engine room for emergency purposes
- Consider multiple redundancy in high radiation areas and where EVA is required
- Provide guards around high temperature equipment and electrical hazards
- Provide protective shielding around dynamic machinery
- Provide fault/failure isolation diagnostic system
- Consider fault diagnosis support from ground systems
- Provide quick disconnect interconnections
- Consider modular replacement of Disposal System
- Consider placement of Disposal electronics within engine room

OPERATIONS

- Do not attempt repair in the gallery area or to the reactor (Considered impractical due to the high radiation levels that exist even after reactor shutdown)
- Do not attempt repair to NaK lines (not considered feasible due to the hazards involved of toxicity, potential fire and radioactivity resulting from NaK activation)

The following major considerations have been analyzed to determine their effects on nuclear safety:

1. Reactor disposal prerequisites; i.e., ability to maintain the reactor subcritical, ability to reduce reactor radiation levels.

2. Disposal mode selection; transfer to high earth orbit, controlled reentry to earth, injection into a heliocentric orbit, destruction, etc.

3. Disposal vehicle selection; manned or unmanned.

4. Reactor disposal analysis; performance requirements, reentry effects, failure modes and effects.

The reference reactor disposal vehicle used in this study is an Integral Disposal Module (IDM) consisting of four solid fuel engines and an independent guidance and navigation system (Figure 7-7). A detailed description of the IDM is presented in Volume III Part 1 of this study.

7.3.4.1 Disposal Prerequisites

The reactor operational status prior to disposal significantly affects the choice of disposal altitude and disposal vehicle. The two dominant considerations are the reactor's criticality status (ability to remain subcritical) and the radiation levels attributed to the fission product inventory. The latter is the controlling factor in determining both the radiation dose level that the disposal vehicle crew will be exposed to, and the orbital lifetime required for fission products to decay to a safe level.

7.3.4.1.1 Reactor Operational Status

It is essential to preclude a reactor criticality accident both during the disposal phase and subsequently during the reentry or earth impact resulting from an accident. The consequence of an excursion occurring could affect the safety of the Space Base crew (see Section 6.2.2.1) disposal vehicle crew and earth's general populace.

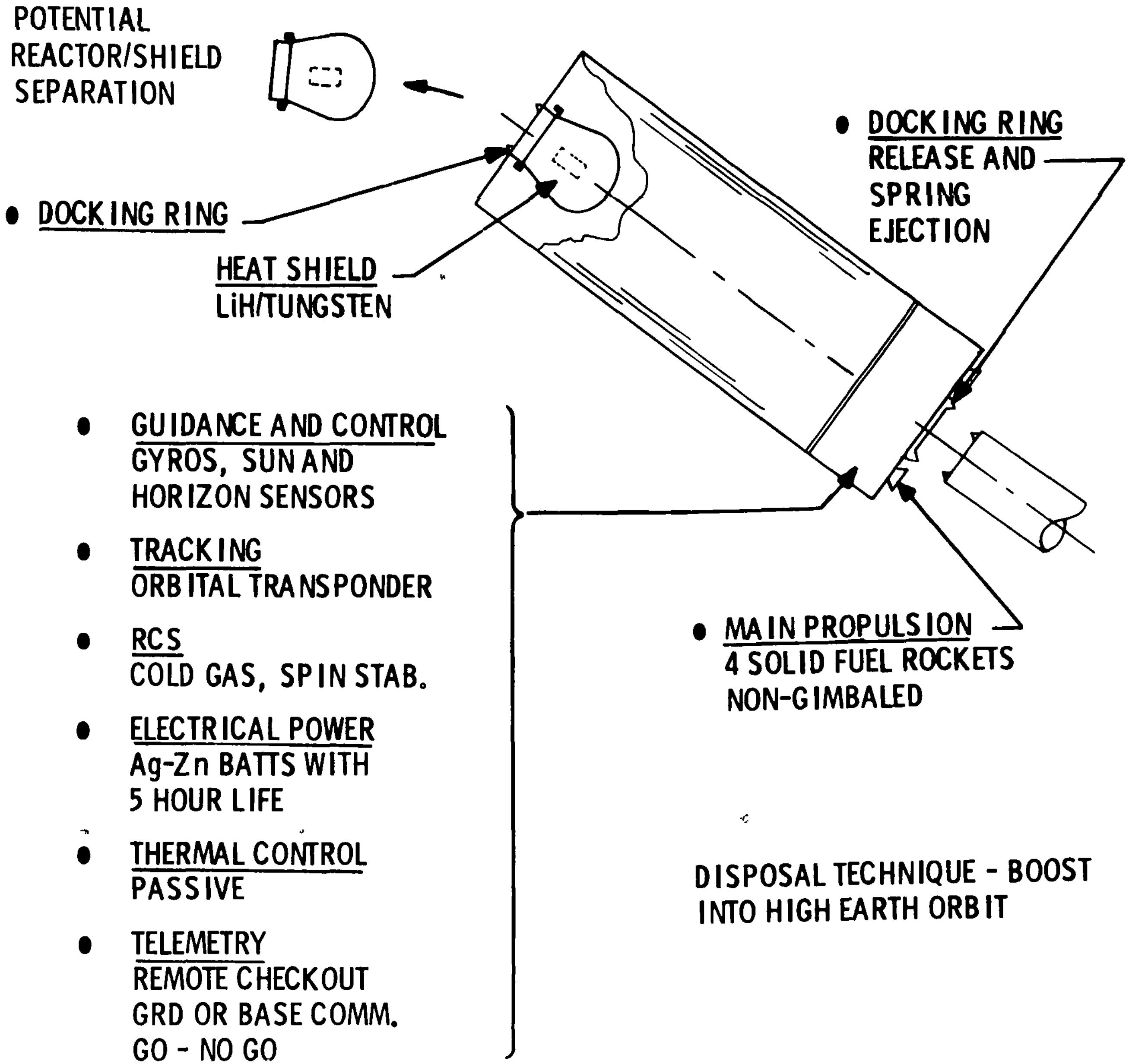


Figure 7-7. Reference Integral Disposal Module

Permanent shutdown of a terrestrial based nuclear reactor is an accepted practice at the end of its operational life. This is accomplished either by: 1) injection of a neutron poison into the coolant; 2) disconnecting and removing the control drum (or rod) drive mechanism; or 3) removal of fuel elements. Removal of fuel elements and control drum drive mechanisms is not practical for the Space Base reactor. Four concepts to maintain permanent reactor shutdown were analyzed. These concepts are:

1. High earth orbit reactor destruct
2. Neutron poison injection
3. Release of the fuel's hydrogen moderator
4. Incorporation of control drum lockout devices.

High Earth Orbit Reactor Destruct - This concept was rejected because it could result in contamination of the upper atmosphere and the ultimate reentry into the earth's environment of radioactive materials.

Neutron Poison Injection - Two concepts for neutron poisoning were considered; injection directly into the core coolant or injection into void tubes located within the core as shown in Figures 7-8 and 7-9 respectively. Maintenance of the poison within the core coolant is dependent upon primary loop containment integrity and therefore is considered less reliable than the injection into void tubes.

Typical poison materials which were considered are hafnium, europium, gadolinum, cadmium and lithium. Cadmium appears to be most promising from melt temperature, neutron cross section and material compatibility aspects. Cadmium with a melt temperature of 594^{o}K can be maintained in a solid state until the time of permanent shutdown to prevent accidental injection during normal operations. It can also be reverted to the solid phase after it has been heated and injected into the core as a liquid. This phase change significantly increases the concept's reliability to maintain the poison within the core during disposal and negates the necessity to maintain absolute primary loop containment integrity.

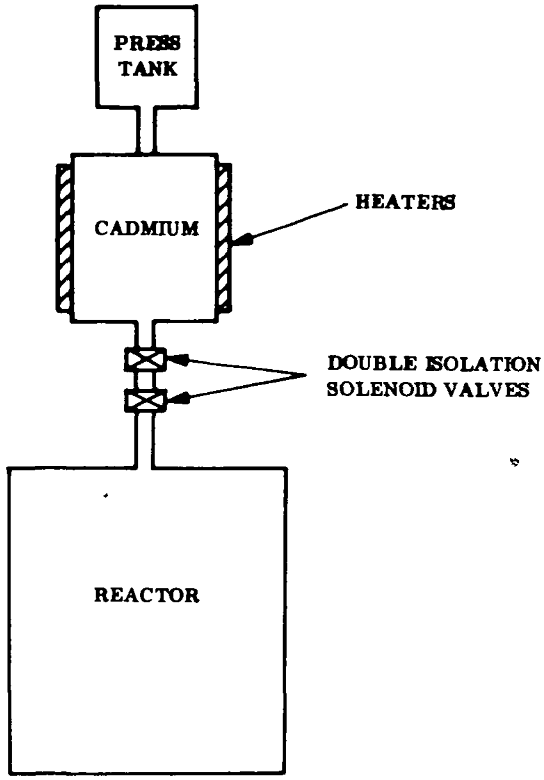


Figure 7-8. Permanent Reactor Shutdown Concept Injection into Coolant

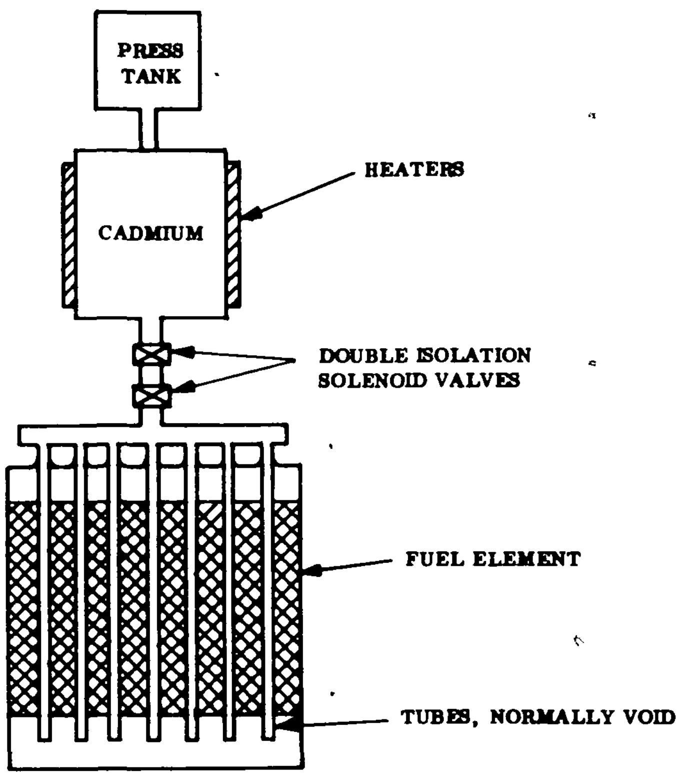


Figure 7-9. Permanent Reactor Shutdown Concept Injection into Void Tubes

It is recognized that the neutron poison injection concept requires extensive design and performance trade-off studies and may have an affect on the operational nuclear safety advantages gained.

Release of the Reactor Fuel's Hydrogen Moderator - Release of the fuel's hydrogen moderator (see Volume III, Part 1, 2 of this report) can be accomplished by raising reactor temperatures to the fuel clad rupture point. One of the main disadvantages of this method is that fission products are released to the coolant and could be released to the environment in the event of a breach in the primary loop containment. Another means of effecting hydrogen release is to cycle the fuel temperature and destroy the integrity of the fuel elements' ceramic barriers thereby accelerating the diffusion of the hydrogen through the clad material. This method allows for retention of fission products within the fuel elements and eliminates the problem of fission product release to the coolant and possibly the environment. Both of these methods were rejected because implementation of procedures to effect hydrogen release could in themselves result in creating unsafe conditions through reactor excursions.

Incorporation of Control Drum Lockout Devices - Control drum lockout devices were first employed in the SNAP-10A flight reactor. Utilization of these devices can serve a dual purpose, (1) prevent inadvertant control drum motion (reactivity insertion) during the ground operations, launch, docking and installation phases of the mission and (2) can be used after permanent shutdown to reduce the probability of a nuclear excursion during the disposal phase of the mission. Figure 7-10 represents a concept of an electro-mechanical lockout device. It is recognized that a five year life requirement is a technical necessity if the devices are to function upon permanent reactor shutdown; however, this is not considered unreasonable since the control drum actuators, which are also electromechanical devices must operate for the same lifetime and in the same environment. Although operational lifetime may be achieved, the lockout devices many not survive an accidental reentry and subsequent earth impact with impact velocities in excess of 244 m/sec (800 ft/sec).

Therefore, a combination of the neutron poison injection and control drum lockout devices appears to offer the highest probability of success in the prevention of nuclear excursions

during the non-operational periods of reactor life.

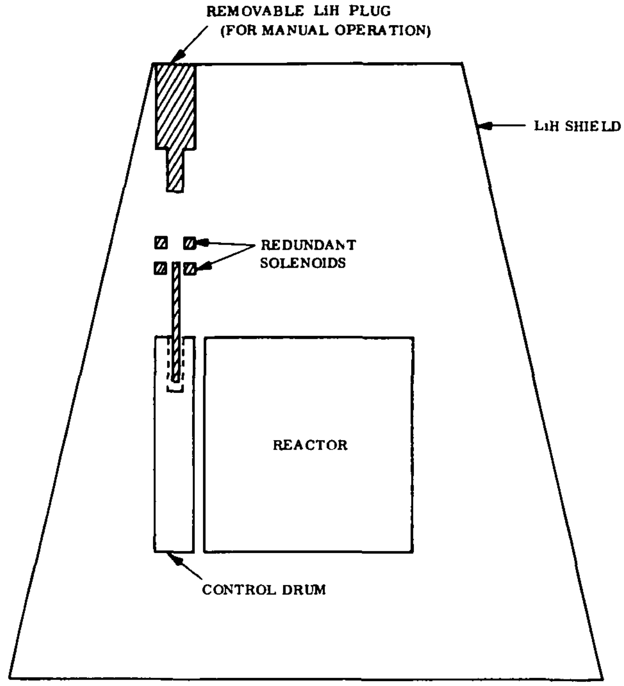


Figure 7-10. Control Drum Lockout Concept

7.3.4.1.2 Reactor Shutdown Radiation Levels

Fission Product Inventory - Fission product inventory is one of the major parameters which dictate the required orbital altitude if transfer to high earth orbit is selected as the prime disposal mode. Figure 7-11 presents data which illustrates typical fission product decay time as a function of fission product inventory. This data is based on the reference Space Base reactor having been operated at a power level of 330 kWt for five years. From this data, an orbital lifetime can be selected that would allow the fission product inventory to decay to a level which would constitute an extremely low, or negligible, hazard upon its ultimate reentry into the earth's atmosphere. For example, an orbital lifetime of 300 years would allow the Sr^{90} inventory to decay to the level of approximately one curie whereas an orbital lifetime in the order of 540 years would further decrease the inventory to approximately 0.001 curies. Once an orbital lifetime is selected that reduces the fission product inventory to accepted values, the disposal vehicle propulsion characteristics and orbital mechanics for placing the reactor in the selected orbit can be determined. (See Section 7.3.4.4 for details.)

Fission Product Decay Radiation - The level of fission product decay radiation emanating from the shutdown reactor is one of the primary parameters which affects selection of the type of disposal vehicle; manned or unmanned. Figure 7-12 illustrates the direct radiation dose rates emanating from the Space Base reactor as a function of time after shutdown. Using this data, the radiation dose rate to a manned disposal vehicle crew located 1.83 m (6 ft) from the center of the reactor, or 0.76 m (2.5 ft) from the surface of the power module, is

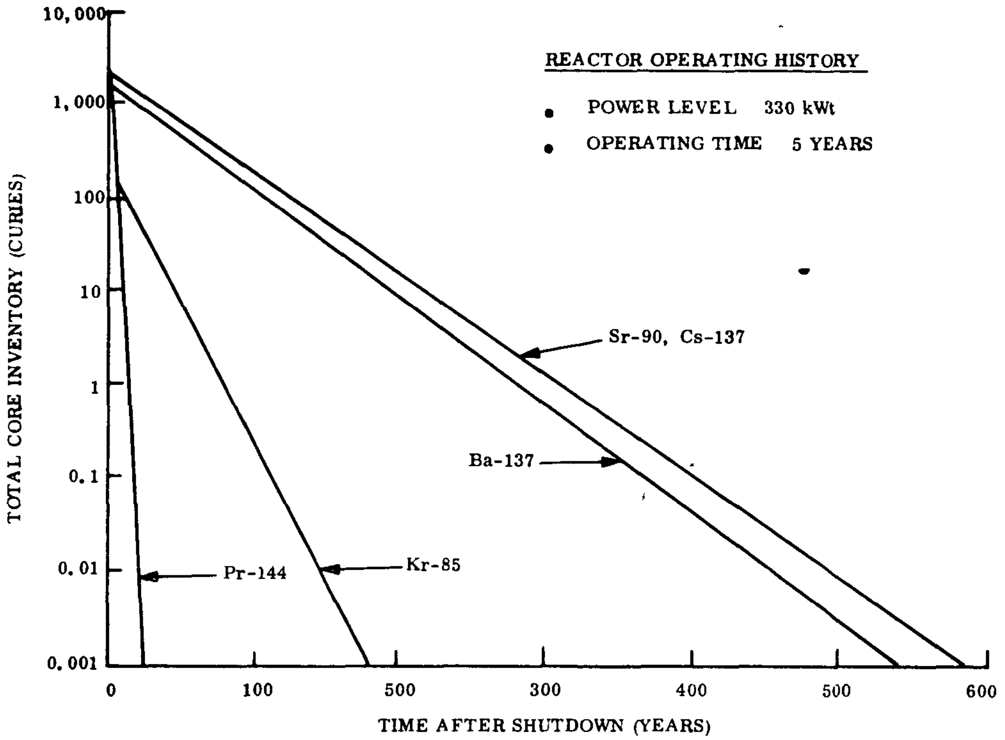


Figure 7-11. Decay of Long-Lived Fission Products Following Reactor Shutdown

approximately 200 rem/hr one day after shutdown. If the mission timeline permits a ten-day waiting period without affecting the Space Base operations, the dose rate is reduced to 900 mrem/hr for the same location; however radiation levels of this magnitude would still require crew radiation shielding for a direct rendezvous approach. Vehicle maneuvering techniques can be developed to reduce the direct radiation dose to the crew. One candidate concept is shown in Figure 7-13. If a manned vehicle could accomplish the rendezvous approach shown in Figure 7-12 the crew dose from direct radiation can be maintained within the allowable 150-200 mrem/day value. However,

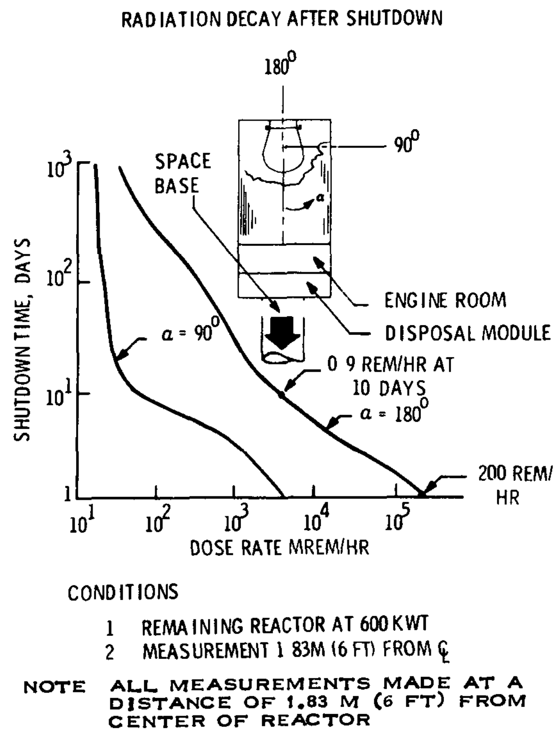


Figure 7-12. Radiation Dose Rate as a Function of Time After Reactor Shutdown

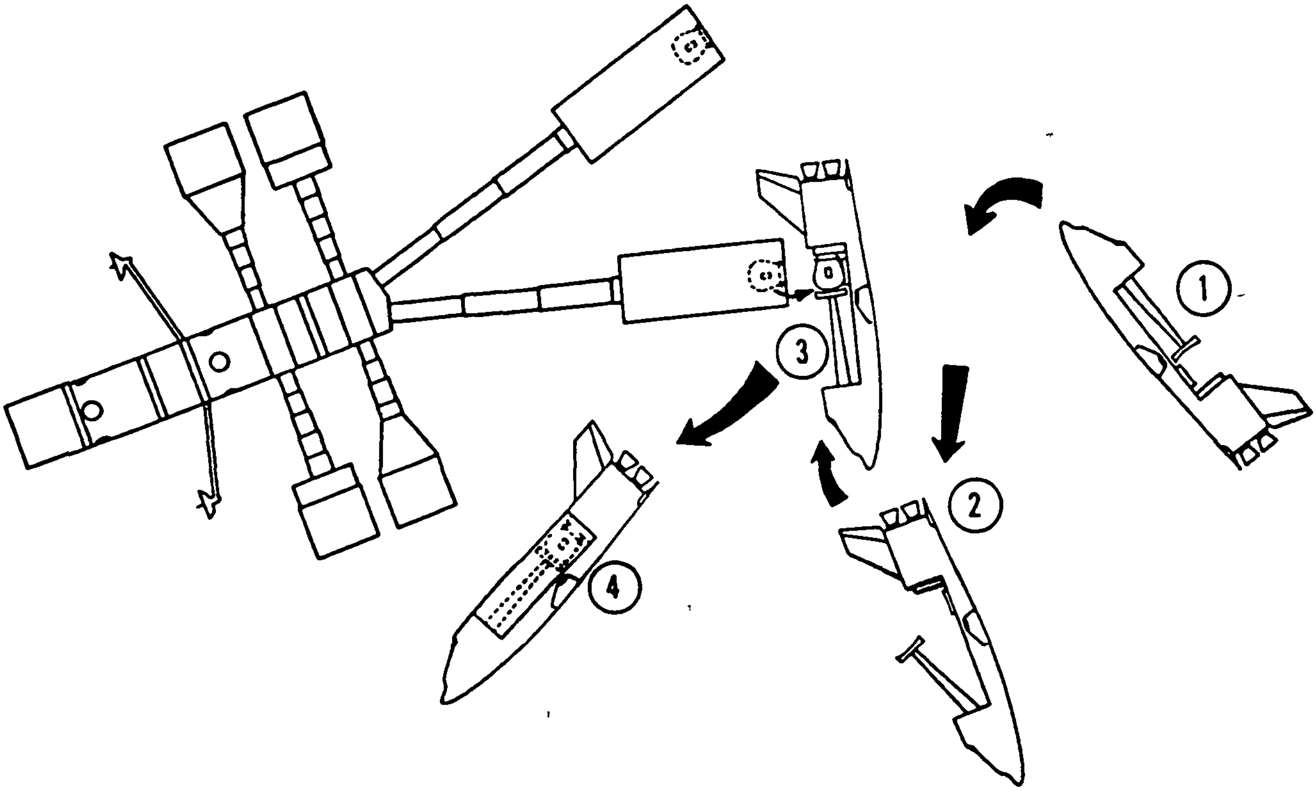


Figure 7-13. Reactor Shuttle Loading Concept

once the reactor/shield is installed in the vehicle cargo bay, assuming it can be separated from the Power Module, the scatter radiation dose becomes the dominant factor rather than direct radiation. Typical scatter radiation dose rates within the Space Shuttle crew quarters were calculated for the assessment of nuclear safety in Space Shuttle operations (Volume IV Part 1 of this study). The results of this analysis are shown in Figure 7-14. These data indicate the crew dose attributed to scatter and direct radiation can be kept below 200 mrem/day, if transfer operations are not initiated until 10 hours after reactor shutdown.

7.3.4.2 Disposal Mode Options

The primary criteria to be considered in determining the optimum disposal mode and location are the safety of the terrestrial population and that of the Space Base crew. The following modes were considered for disposal of the Space Base reactors:

1. Controlled reentry - ocean burial

2. Controlled reentry - land recovery

3. Orbital destruction

4. Injection into heliocentric orbit

5. Transfer to high earth orbit

Natural earth orbital decay, "random reentry", was not considered a planned reentry mode, but was evaluated to determine the effects of aborted disposals resulting from the disposal modes and locations identified above (see Section 7.3.4.4).

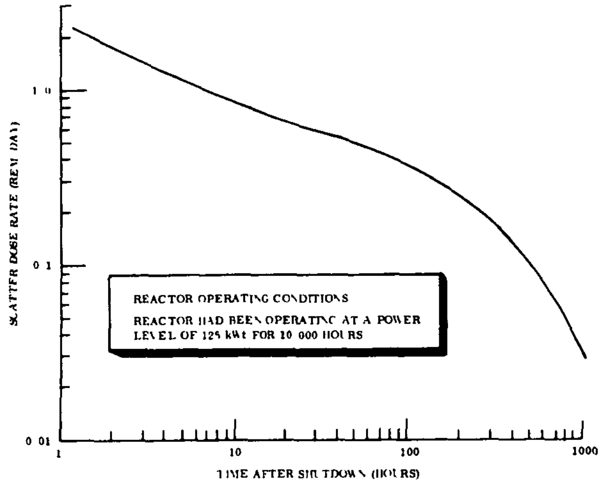


Figure 7-14. Reactor Scatter Dose Rates While Stowed in Shuttle Cargo Bay

Controlled Reentry - Controlled reentry by unmanned vehicles with either a land recovery or ocean burial could present a serious hazard to the terrestrial population in the event of a mission abort. Consequently, highly reliable systems, capable of performing the following functions are necessary:

1. Prevention of burnup and disassembly during reentry.

2. Control of impact point with a high degree of confidence.

3. Prevention of reactor disassembly upon impact.

Controlled reentry, where another vehicle such as the Space Shuttle provides the reentry capability, appears to be more promising as a disposal method because of the crew's ability to respond to emergency situations but requires further detailed study (Reference Volume IV, Part 1) to assess the consequences of abort accidents such as reentry burnup and propulsion, guidance or landing system failures. This mode was retained as a backup for the disposal of a reactor.

Orbital Destruction - Earth orbital destruction of a reactor was rejected as a disposal mode because it may result in immediate or long-term contamination of the upper atmosphere, terrestrial environment and general populace. Furthermore, the resultant radioactive debris may effect other satellites, experiments and the Space Base crew.

Injection into Heliocentric Orbit - Injection into a heliocentric orbit theoretically provides an infinite orbital lifetime which precludes any possibility of radiological hazards to earth and the upper atmosphere. In order to inject the PM weighing 31.8t (70 klb) into such an orbit, a ΔV of approximately 3.14 km/sec (10,300 ft/sec) would be required. The solid propellant mass for such a maneuver would be approximately 66.5t (168.5 klb). This mass penalty was considered too great to justify further consideration of this disposal mode.

Transfer to High Earth Orbit - Early in the study it became apparent that transfer of the reactor to high earth orbit would provide a means to significantly reduce the radiological risk associated with reactor disposal. A successful transfer can be considered negligible when the reactor ultimately reenters. This mode was selected as the baseline to evaluate candidate disposal implementation methods.

7.3.4.3 Candidate Disposal Vehicles

The candidate disposal vehicles that can be utilized for the preferred disposal mode of transfer to high earth orbit are manned disposal vehicles (e.g., Space Shuttle, Space Tug), the Integral Disposal Module (IDM) and unmanned versions of the Space Tug.

7.3.4.3.1 Manned Disposal Vehicles

Two of NASA's (candidate) advanced vehicles, the Space Shuttle and Space Tug (Reference 7-9) may be used for the disposal of spent space reactors. Manned disposal vehicles offer the following advantages:

1. High probability of mission success since crew members can respond and correct for system malfunctions.

2. Flexibility in selecting disposal location, since the manned vehicle can be used to either transfer the reactor directly to high earth orbit, or, in the case of the Shuttle, act in a backup mode to retrieve and return the reactor to earth in the event of an orbit transfer abort.

Both the Shuttle and the manned Space Tug are expected to have the capability to transfer a reactor or power module to a high orbit for disposal (Reference 7-7). Volume IV, Part I of this report discussed the Nuclear Safety aspects of using the Shuttle for Nuclear System Transportation.

7.3.4.3.2 Unmanned Disposal Vehicles

Two types of unmanned disposal vehicles have been considered: (1) Integral Disposal Modules that are part of the Power Module structure and (2) Vehicles, such as the unmanned version of the Space Tug, which have propulsion and maneuvering capability and are mated to the spent reactor at the time of disposal initiation.

Integral Disposal Module - The IDM, shown conceptually in Figure 7-7, has intrinsic characteristics which influence nuclear safety. The primary advantage, over other vehicles considered, is the ability to accomplish immediate disposal of the reactor during any mission phase since it is integral with the Power Module structure. Therefore, the reactor disposal may be accomplished inthe event of a reactor accident or a Space Base abort situation, without reliance on an independent support vehicle. Because of the importance of the disposal function, the IDM must be an extremely reliable unit. The projected reactor lifetimes require that the IDM be capable of reliably performing after mission durations of up to five years. Therefore, the IDM must incorporate design features such as redundancy, and strategic radiation shielding of sensitive components, to assure reliability. Periodic functional checkout, maintenance and repair must also be scheduled during the mission, since repair will be difficult once the power module has been separated from the Space Base.

Unmanned Tug - This concept is envisioned as a vehicle with guidance, propulsion and docking capability, which would be controlled from the Space Base or through ground networks. A recent tug concept, provides for separation of the crew module of the manned tug, and remote operation of the remaining portion of the vehicle (Reference 7-9).

Employing an unmanned tug for reactor disposal appears very attractive from a nuclear safety standpoint. It provides a portion of the flexibility exhibited by the manned vehicles while eliminating the radiological hazards to which the crew of these vehicles could be exposed. It also partially circumvents the long life required with the IDM concept. As presently conceived the unmanned Tug, could be either stored on-board the Space Base or launched by the Shuttle. Therefore, the repair and checkout of guidance and disposal engines could be accomplished immediately prior to its use as a disposal vehicle.

The exclusive use of the unmanned Tug as a disposal system negates the IDM advantage of immediate separation of the power module in the event of an accident. Therefore, system concepts employing the Tug for disposal should also include provisions for quick separation of the power module from the Space Base and the development of techniques for the recovery in the event of subsequent power module tumbling. These latter features would provide contingency capabilities in the event of emergency situations associated with the power module.

7.3.4.4 Reactor Disposal Analyses

An analysis of the disposal of a reactor to high earth orbit was performed to determine the following:

1. Performance requirements of the disposal vehicle.
2. Orbital lifetimes of the baseline power module and of a separated reactor-shield.
3. Effects of a disposal module abort during the transfer (Hohmann transfer).
4. Reentry characteristics of the power module assuming the aborted transfer results in earth reentry.

The analysis is based on the use of the reference Integral Disposal Module although it is also applicable to the unmanned Space Tug concepts.

7.3.4.4.1 Vehicle Performance Requirements

A parametric orbital mechanics analysis was performed to determine the following:

1. Amount of disposal vehicle fuel and the ΔV required to attain orbits between 741 km (400 nm) and 1298 km (700 nm) and injection into a heliocentric orbit.

2. Orbital lifetimes for each of these orbits were calculated as a function of varying solar flux and ballistic coefficients. The orbital lifetime of an abandoned Space Base was also determined.

3. The orbital life sensitivity to engine abort was also determined on the basis of a Hohmann Transfer.

Vehicle Performance - The ΔV required to boost the power module, 31.8t (70 Klb) to various orbits is shown in Table 7-19. The analysis assumed the power module had been separated from the Space Base by ejection springs. Transfer to a higher orbit consists of two propulsive maneuvers· (1) a thrust from the reference orbit to the selected transfer orbit, and (2) a thrust at apogee to affect circularization at the disposal attitude.

As shown in the data, the mass penalty incurred for injection into heliocentric orbit is 76t (168.5 Klb) for a solid fuel booster. This penalty was considered too great and was one of the prime reasons for rejection of a heliocentric orbit as a disposal mode.

Orbital Lifetime - The orbital lifetimes and associated altitudes presented in Table 7-19 differ from those used for the radiological risk asseessment presented in Volume III, Part 3 of the study. The basis of this difference is that the most conservative solar flux model available was used in the risk assessment analysis whereas this analysis is based on a solar flux model prepared by the Lockheed Corporation for the NASA's George C. Marshall Flight Center (see Appendix E for details).

One of the pertinent results of this analysis is the significance of being able to separate the reactor/shield from the power module. The orbital lifetime of the reactor-shield can be increased by approximately a factor of nine (9) if a separable heat exchanger or similar means were available to accomplish separation.

Also of significance is the fact that if the Space Base is abandoned, with the power modules still attached, the associated earth orbital lifetime of 5-18 years will allow for implementation of emergency procedures for reactor recovery and disposal.

Table 7-19. Critical Parameters Effecting Power Module Disposal

Orbit	Altitude km	Altitude (nm)	Total ΔV (2) $\frac{m}{sec}$	Total ΔV (2) $(\frac{ft}{sec})$	Fuel Wgt. (1) kg	Fuel Wgt. (1) (lbs)	Orbital Lifetime (Years): POWER MODULE - (4) $\beta = 1905 \frac{\text{Newtons}}{m^2}$ ($\beta = 39.8\ lbs/ft^2$) Maximum (3)	POWER MODULE Minimum (3)	REACTOR/SHIELD - $\beta = 16,853 \frac{\text{Newtons}}{m^2}$ ($\beta = 352\ lbs/ft^2$) Maximum (3)	REACTOR/SHIELD Minimum (3)
Reference	500	(273)	N/A		N/A		27	7.75	240	68.5
Circular	741	(400)	129	(425)	1,643	(3,622)	637	246	6,190	2,170
↓	927	(500)	226	(740)	2,922	(6,443)	7,090	2,534	62,800	22,400
	1298	(700)	401	(1315)	5,370	(11,842)	627,700	223,600	5×10^6	2×10^6
Heliocentric	N/A		3,139	(10,300)	76,000	(168,500)	∞	∞	∞	∞
SPACE BASE ORBITAL LIFE IF ABANDONED 5-18 YEARS										

ORBITAL SENSITIVITY TO ENGINE ABROT FOR 925 km (500nm) DISPOSAL ORBIT

Elliptical	927	(500)	116	(380)	2,921	(6,443)	200	72	1,772	632
Circular	927	(500)	110	(360)			7,090	2,534	62,800	22,400

(1) Specific Impulse = 260 Seconds, Solid Propellent
(2) Hohmann Transfer
(3) Maximum to Minimum variation due to Solar Flux
(4) β = Ballistic Coefficient

Orbit Sensitivity to Engine Abort - Table 7-19 illustrates the sensitivity of an engine abort occurring if the first thrust firing is successful and the engines do not fire for the second thrusting (orbit circularization). If worst case conditions are assumed, an orbit lifetime of 72 years can be attained for the power module in a 927 km (500 nm) elliptical orbit.

The analysis also indicates that immediate direct reentry of the reactor does not occur if the guidance system malfunctions for the second thrust firing, but instead results in a highly elliptical orbit. Guidance system malfunctions for the first thrust firing at the reference Space Base orbit result in direct immediate reentry for firing angles between -90^{o} and -180^{o} from the horizontal. However, most of the guidance abort cases considered result in elliptical orbits with orbital lifetimes longer than that of the Space Base orbit altitude. For those few cases resulting in immediate earth reentry, a reentry analysis was performed to determine reactor survivability. (See Appendix E for details of engine and guidance system malfunctions.)

7.3.4.4.2 Reactor Reentry Analysis

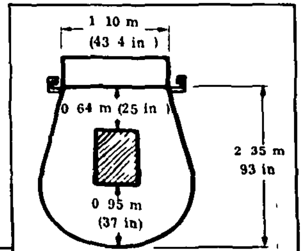
A reactor reentry analysis was performed to determine the power module and reactor-shield reentry characteristics. The analyses included consideration of the following postulated disposal abort conditions:

1. Power module guidance system fails on first thrust firing and power module reenters.
2. Power module engines do not fire for circularization burn and the power module reenters in a normal earth orbital decay (EOD) mode.
3. Power module guidance system failure which results in an elliptical orbit and eventual EOD (same reentry as item 2).
4. Power module reentry from a circular orbit, normal EOD.

A summary of this analysis and the resulting principal parameters are presented in Table 7-20 which includes three of the basic reentry configurations:

1. Earth orbital decay of the reactor-shield.

Table 7-20. Reentry Analysis



Reentry Parameters

	Configuration	β* Neutons/m^2 $\left(\frac{lb}{ft^2}\right)$	Type of Re-entry	Peak Heating kWt/m^2 $\left(\frac{BTU}{ft^2 - sec}\right)$	Peak Heating Altitude m (ft)	Integrated Heating Joules/m^2 $\left(\frac{BTU}{ft^2}\right)$	Impact Velocity m/sec (ft/sec)
1		82 114 (1715)	Earth Orbit Decay	4,222 (372)	35,052 (115 000)	1 371 x 10^6 (116 000)	524 (1720)
2	Release and Skip 	5,506 (115) 82 114 (1715)	Earth Orbit Decay	2,043 (180) PM 4 222 (372) Reactor Shield	35 052 (115,000)	1 371 x 10^6 (116 000)	238 (782) Tumbling
3	Release 	5,506 (115) 82,114 (1715)	ΔV Reentry M/sec ft/sec Angle 401 (1315) - 2^o 226 (740) - 2^o 401 (1315) - 4^o **	 4,983 (439) 5,227 (487) 7,934 (699)	 29 261 (96,000) 28,651 (94 000) 25 298 (83 000)	 81 200 x 10^6 (72,300) 47,500 x 10^6 (65 700) 45,400 x 10^6 (40 000)	 480 (1576) 479 (1571) 479 (1572)

*Ballistic Coefficient
**ΔV Reentry occurs when Guidance System fails in first thrust firing resulting in direct reentry of the power module

2. Earth orbital decay of the power module with release of the reactor-shield from the power module at an altitude of approximately 98 km (320,000 ft).

3. Reentry of the power module resulting from a successful first thrust firing and failure of the power module g

The worst case reentry conditions result from configuration (3) which sequentially lead to a release of the reactor/shield from the power module at a nominal altitude of 98 km and skip out of the reactor-shield due to the change in ballistic coefficient from 5.506 N/m^2 (115 lbs/ft^2) to 82.114 N/m^2 (1715 lbs/ft^2). The summarized data for configuration (3) also includes two different reentry angles -2^o and -4^o, and two initial power module thrust velocities, a ΔV of 401 m/sec (1315 ft/sec) and a ΔV of 226 m/sec (740 ft/sec). These velocities represent the total thrust required to boost the power module from the reference Space Base orbit to disposal altitudes of 1298 km (700 nm) and 927 km (500 nm), respectively. To provide for worst case conditions, results are shown for the case where all four disposal engines fire simultaneously due to a malfunction rather than the two required for the first thrust and then two for the circularization thrust.

The analysis also included a variation in reentry orientations such as:

1. Power module end-on and side-on
2. Reactor/shield end-on; gallery end first and gallery end backward
3. Reactor/shield side-on
4. Reactor/shield tumbling
5. Space Base end-on and side-on

(Refer to Figure 7-15 for orientation definition.)

The analyses indicate that if the Space Base is abandoned and reenters through the normal earth orbital decay, the reactor/shield reentry and release altitude is similar to that of

the power module EOD mode with the reactor/ shield being released from the power module at 98 km (320 Kft).

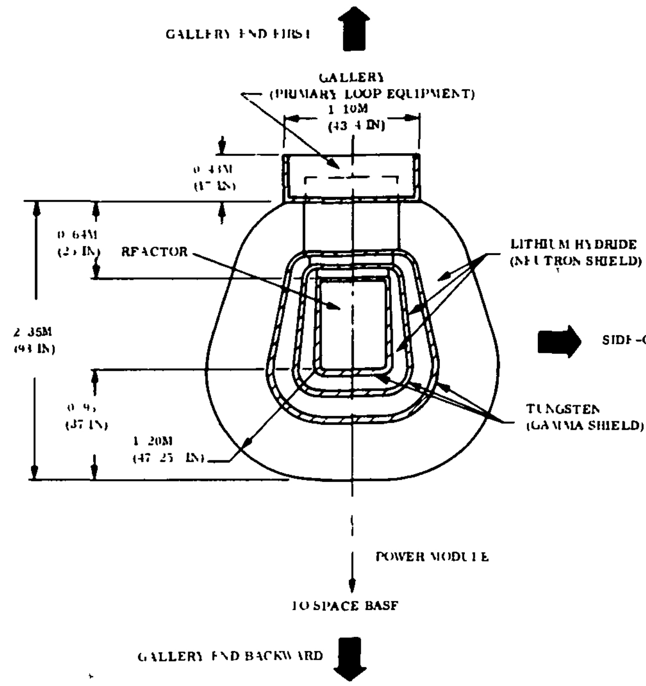
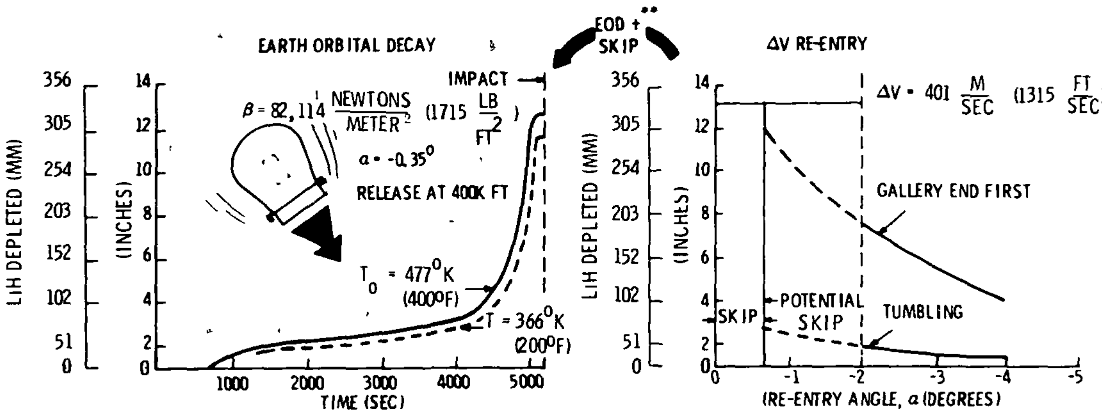


Figure 7-15. Reactor/Shield Combination

Lithium Hydride ablation calculations were also performed. Figure 7-16 illustrates the amount of LiH which is ablated for reentry conditions. The worst case condition occurs when the power module reenters after a first thrust firing, the reactor/shield skips out of the atmosphere and ablates away some of the LiH on each skip, and ultimately reenters in a EOD mode in a stable gallery-end-first orientation. The exact amount of LiH which ablates is difficult to calculate since it is dependent on the number of skips and the depth of penetration into the atmosphere for each skip. However, since a normal EOD, stable gallery-end-first orientation results in ablation of 318 mm (12.5 in.) of the 640 mm (25 in.) protecting the reactor, it can be safely assumed that the total amount of LiH ablated would be in excess of 318 mm. The curve on the right (in Figure 7-16) is the potential of skip for a ΔV reentry of 40m/sec (1315 ft/sec) as a function of reentry angle. Trajectory calculations predict the reactor/shield will skip out for angles of 0 to -0.75° with a potential for skip from -0.75° to -2.0°, but direct reentry does occur for angles beyond -2.0°.

The comparative difference in ablation of LiH for a stable-gallery-end-first and a tumbling orientation is also shown in Figure 7-16. A tumbling orientation results in only 81 mm (2.65 in.) of ablation compared to the 318 mm of the stable gallery end-on orientation.

The influence of initial LiH temperature (at the beginning of reentry) was assessed. This is a function of the reactor decay heat and time of reentry after reactor shutdown. The data presented in Figure 7-16 shows a ΔT of $111^{\circ}K$ $(200^{\circ}F)$ changes the amount of LiH which is ablated by approximately 10%. The first condition assumed an initial temperature of



- * ΔV REENTRY OCCURS WHEN GUIDANCE SYSTEM FAILS IN FIRST THRUST FIRING RESULTING IN DIRECT REENTRY OF POWER MODULE.
- ** SKIP OCCURS AS A RESULT OF A ΔV REENTRY WHEN THE REACTOR-SHIELD IS RELEASED FROM THE POWER MODULE AT 320 KFT AND SKIPS OUT OF THE ATMOSPHERE DUE TO THE LARGE CHANGE IN BALLISTIC COEFFICIENT AND SUBSEQUENTLY REENTERS IN AN EOD MODE.

SUMMARY OF RESULTS

TYPE OF REENTRY	LiH DEPLETED
ΔV = 401 M/SEC (1315 FT/SEC), -2°	193 MM (7 6 IN)
EOD	318 MM (12 5 IN)
ΔV - SKIP - EOD	318 + MM (12 5 + IN.)

Figure 7-16. Earth Orbital Decay and Aborted ΔV Reentry Analysis

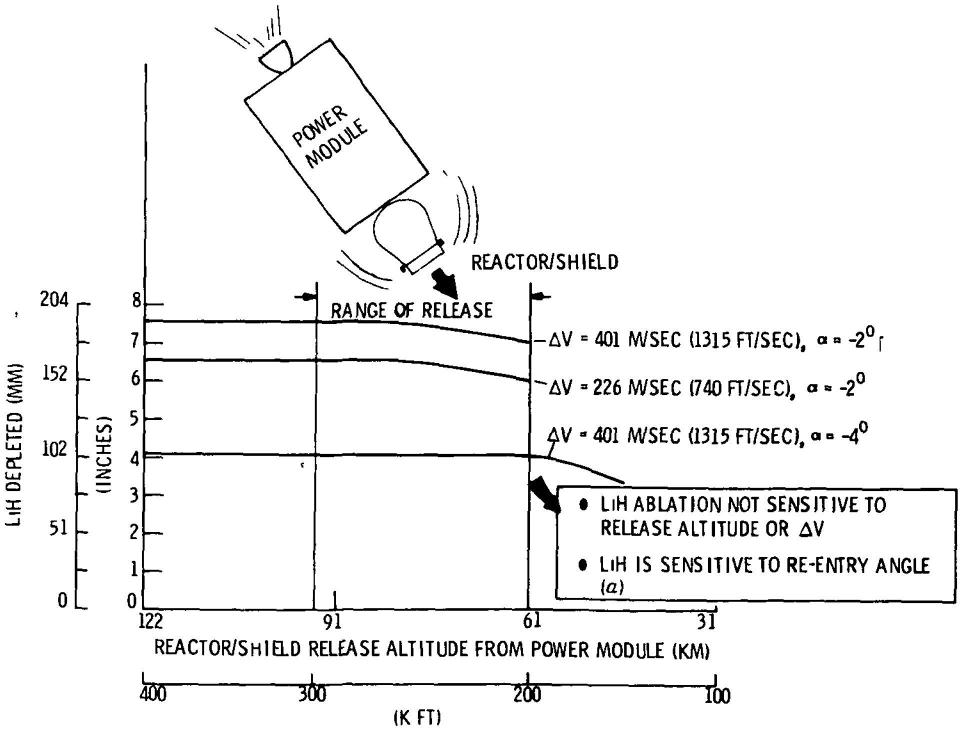


Figure 7-17. Reentry Sensitivity to ΔV Release Altitude and Angle (α)

$T_o = 477^oK$ (400^oF) and the second a $T_o = 366^oK$ (200^oF). The LiH temperature would be significantly affected by the incorporation of an independent reentry shield since the current means of rejecting the decay heat is by radiation (assuming primary coolant loop is inactive). Incorporation of an independent heat shield would most likely utilize an insulating material between the reentry shield and that LiH thereby necessitating an independent LiH cooling system.

The power module reentry sensitivity to (1) the ΔV (engine thrust) impacted for aborted transfers, (2) the altitude at which the reactor/shield is released from the power module and (3) the reentry angle, is illustrated in Figure 7-17. The conclusions derived from this data are that the amount of LiH ablated during reentry is:

1. Relatively insensitive to the altitude at which the reactor/shield is released from the power module.

2. Slightly sensitive to the initial thrust firing velocity. Note that for a factor of almost two change in ΔV, 401 m/sec to 226 m/sec, the amount of LiH ablated changes by approximately 10%.

3. Very sensitive to the initial reentry angle. Doubling the reentry angle, -2^o to -4^o, increases the amount of LiH ablated by a factor of almost two (2) for the same ΔV.

The results of the reentry analysis presented so far indicate that for the worst case reentry, reactor/shield skip and ultimate EOD, results in ablation of more than 318 mm (12.5 in.) of the 640 mm (25 in.) of LiH protecting the reactor. The analysis was based on the following assumptions:

1. The shield was composed of all LiH encapsulated with 31 mm (0.10 in.) of stainless steel. The layers of tungsten shown in Figure 7-15 were not included due to complexities introduced to the analysis and the uncertain behavior (requires an experimental test program) of the tungsten-LiH composite. The tungsten will probably oxidize and also re-radiate some of the thermal energy. However, its high melt temperature, $3,643^oK$ ($6,030^oF$) can adversely affect the reentry. Since LiH melts at 961^oK (1270^oF) it will melt long before the tungsten reaches its melt point, expand and increase its internal pressure. The effect of the increased pressure on the tungsten and the possible interactions between molten lithium, liberated hydrogen and the tungsten are unkonwns which may affect the reentry. Resolution of this problem was beyond the scope of this study.

Plasma arc tunnel tests of LiH specimens had previously been performed by General Electric. These tests indicate that the LiH ablation rate is a factor of 2-3 greater than predicted by analysis for less severe environmental conditions. The results of these tests are shown in Figure 7-18 and are discussed in more detail in Volume III, Part 2 of this study, as is the reentry analysis.

Applications of these results to the reentry analysis could result in the ablation of all the 640mm (25 in.) LiH protecting the reactor during reentry and result in exposure of the reactor core and fuel to the reentry environment.

7.3.4.5 Conclusions

The conclusions presented here are based on nuclear safety aspects and require further consideration to define those technologies (e.g., reactor poison injection), which are expected to significantly contribute to the safe disposal of a reactor power module. These conclusions are:

1. A positive means of reactor shutdown is desirable to further minimize criticality accidents resulting from disposal operations. The neutron poison injection concept has been used on terrestrial commercial reactors and is recommended for the reference reactor.

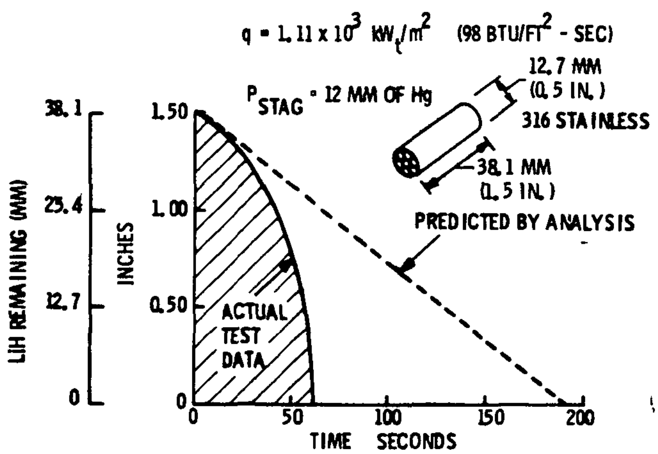


Figure 7-18. LiH Specimen Reentry Test Results

2. Intact reentry of a conventional LiH shield is questionable for many of the reentry modes which were considered for the Space Base application. Prior to this study, LiH was utilized predominantly as a radiation shield and considered acceptable as a reentry protection material. Results of this study indicate the need for an independent reentry protection system.

3. Separation of the reactor/shield from the PM would significantly increase orbital lifetimes, i.e., increases ballistic coefficient. Inclusions of a separable heat exchanger in the PM design is one means of providing a separation capability. It also allows for replacement of the reactor/shield without having to replace the entire PM.

2. The location and orientation of the primary cooling piping is not established for the reference design. Consequently, the analysis did not account for this. However, it will most certainly penetrate the LiH and each layer of tungsten from the reactor to the gallery (see Figure 7-15). The total effect of these penetrations on the reactor/shield aerodynamic characteristics and the reentry behavior of the LiH will probably adversely affect the reentry.

3. It was assumed that thermal energy created during reentry is absorbed by the LiH heat capacity, i.e., its sensible heat ($WC_p \Delta \bar{t}$) and latent heat of fusion. Recent experimental tests by the NASA, Ames Laboratories and the General Electric Company indicate LiH dissociates at its melt temperature, into free Li and H_2 which oxidize. The General Electric study shows that the oxidation produces exothermic reactions which liberate energy in the order of 55.8×10^6 joules/kg of LiH (24,000 Btu/lb of LiH). In considering the most optimistic reentry characteristics of LiH the heat capacity of LiH consists of its sensible heat, latent heat of fusion, heat of dissociation and the vapor blocking contribution. Arbitrarily assuming an initial LiH temperature of 427°K (300°F) the total heat capacity is calculated to be approximately 31.7×10^6 joules/kg of LiH (13,635 Btu/lb of LiH; the individual components of this term are:

		Joules/Kg of LiH	Btu/lb of LiH
Sensible heat	=	3.4×10^6	(1475)
Latent heat	=	2.9×10^6	(1250)
Heat of dissociation	=	11.4×10^6	(4910)
Vapor blocking contribution	=	14.0×10^6	(6000)
Total		31.7×10^6	13,635

The heat capacity arrived at may be highly optimistic depending upon the actual behavior of the LiH during the reentry process. For example, if the LiH melts and is forced into the free stream in droplet form without dissociating, the effective heat capacity could be reduced to the sum of the sensible heat and latent heat of fusion, 6.34×10^6 joules/kg (2,725 Btu/lb)of LiH.

Both experimental and analytical studies conducted by the General Electric Company with graphite have indicated that for certain reentry configurations, virtually all of the heat released by exothermic reactions in the boundary layer is transferred back to the reentering body. There is no evidence to suggest that this phenomena is indicative only of graphite and it would appear that the theory can be extended to other reentering bodies having reacting gas boundary layers. It is probable that some percentage of the energy liberated by the exothermic reactions, 55.8×10^6 joules/kg of LiH (24,000 Btu/lb) will be transferred back to the reactor shield.

4. Transfer to high earth orbit provides time for decay of fission products. Orbital lifetimes in the order of 250 years allow for fission product decay to levels that are below generally accepted safe levels.

5. The unmanned Tug appears to offer promising safety advantages for disposal of spent reactors. It eliminates any potential problem of radiological hazards to a crew, provides flexibility in the selection of disposal location, and can be checked out in free flight prior to attachment to the reactor.

6. Safe disposal of a damaged reactor (activated coolant or fission products are released) is greatly enhanced by use of the unmanned Tug.

7.4 REFERENCES

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SECTION 8

RESEARCH AND TECHNOLOGY IMPLICATIONS

KEY CONTRIBUTORS

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SECTION 8
RESEARCH AND TECHNOLOGY IMPLICATIONS

The general design and operations considerations discussed in this volume will require additional study and evaluation to establish the specific means of implementation on future programs. In addition to these studies, which will be conducted as part of the normal design evolution of a program, several particular areas of research and technology development are required which have a major impact on nuclear safety both in space and on the earth.

The areas identified and discussed in some detail below include:

1. Launch Support Requirements - Nuclear Hardware Impact
2. Liquid Metal Support Requirements - Impact at Launch Center
3. Launch Support Fire Protection - Nuclear Hardware Impact
4. Nuclear Reactor/Power Module Separation
5. Reactor Protection Technology
6. Blast and Fragmentation Protection - Schemes and Estimation Models
7. Reactor Permanent Shutdown
8. Nuclear Debris In-Orbit
9. In-Orbit Decontamination Techniques
10. Space Qualified Radiation Monitoring Equipment
11. Standardization of Safety Analysis Techniques

8.1 LAUNCH SUPPORT REQUIREMENTS - NUCLEAR HARDWARE IMPACT

8.1.1 OBJECTIVES/REQUIREMENTS

The analysis associated with this study (especially those contained in Section 5) identify the general facility requirements for the handling and preparation of nuclear hardware at the

launch center. These requirements have been defined based on the nuclear safety needs of a single program, but have not considered schedule, technical, cost and joint usage aspects in the implementation of the total nuclear facility requirements.

The prime objective of such a study shall be to study and identify the projected facility needs such that a plan can be implemented which makes maximum usage of existing facilities. In addition, new facilities required can be designed with future growth capability and serve multiple usages.

8.1.2 APPROACH

The projected needs of future nuclear programs should be evaluated to establish a plan for meeting the expanding use of nuclear power systems and hardware in the coming decades. These studies should consider the use of isotope as well as reactor systems. A thorough study of the hazards involved and current methods employed at nuclear facilities to implement safety is required. A review of existing facilities should be made to identify potential usage and the additional requirements necessary to allow usage as nuclear facilities. The scope of the study should consider the risk-gain trade-offs of nuclear activities which would be allowed in existing facilities versus modifications necessary for obtaining special licenses or the need for a completely new facility. Cost, schedules and facility and personnel risk factors should be considered. An example of such a study is the potential use of the VAB as an assembly and integration area for nuclear power systems versus the bypassing of the facility with final integration at the launch pad. The latter approach requires a separate checkout and assembly facility.

An additional study area could involve a preliminary identification of nuclear hardware operational procedures to determine the impact on launch operations.

8.2 LIQUID METAL SUPPORT REQUIREMENTS - IMPACT AT LAUNCH CENTER

8.2.1 OBJECTIVES/REQUIREMENTS

Reactor power systems for space applications use significant quantities of liquid metal coolant. The safe handling and servicing of this hardware and liquid metal inventory must be provided at the launch center. The facility and procedural requirements necessary for the support of future programs shall be identified such that results can be factored into future plans, budgets and schedules.

8.2.2 APPROACH

The projected liquid metal servicing and handling needs of future nuclear programs should be evaluated. The study should consist of a thorough review of the hazards involved in the handling of liquid metals and the techniques used at existing facilities around the country. The requirements for the safe handling of liquid metals at the launch center should be established.

A review of existing facilities at the launch center should be made to identify compatibility with liquid metal handling and safety requirements. Special facility requirements such as isolated chambers, environmental protection and fire protection shall be identified. Modifications to existing facilities shall be proposed and new facility requirements identified. Trade-offs should include the advantages of a full charging and unloading/safing facility versus a minimum facility whereby liquid metal charging must be done at the factory. Preliminary procedures should be developed to identify the potential impact on launch operations. Costs and schedules should be developed for budgetary and planning purposes.

8.3 LAUNCH SUPPORT FIRE PROTECTION - NUCLEAR HARDWARE IMPACT

8.3.1 OBJECTIVES/REQUIREMENTS

Section 5 of the study indicates the requirements for fire protection at the Launch Complex and indicates the possible incompatibility between conventional fire protection techniques and materials and characteristics of the nuclear/liquid metal hardware. Present fire

protection methods rely extensively on water deluge and sprinkler systems. However, water and other common fire extinguishing solutions are not compatible with liquid metal fires. Furthermore, the reference reactor may pose a hazard when submerged in water under certain conditions (see Volume III-Part 2). The objective of the study shall be to identify fire protection techniques and possible technology programs which have as a goal the compatibility with nuclear hardware at the launch pad,assembly and storage facilities.

8.3.2 APPROACH

Fire protection requirements and currently employed concepts at nuclear and liquid metal facilities would be identified. Current fire protection provisions at applicable launch complex facilities would be evaluated for compatibility and compliance with nuclear hardware requirements. Application of currently employed nuclear/liquid metal fire protection techniques to the launch complex and the resulting impact on existing facilities and flight hardware would be evaluated. Modifications to existing procedures and facilities would be proposed. Where definite incompatibilities exist which cannot be resolved by utilizing available techniques, studies must be pursued to identify new techniques. These techniques would be candidates for a technology development program.

8.4 NUCLEAR REACTOR/POWER MODULE SEPARATION

8.4.1 OBJECTIVES/REQUIREMENT

The capability of separating the reactor/shield assembly from the power module assembly has been shown to be a significant means of enhancing nuclear safety. The analyses performed in evaluating reactor disposal techniques (Section 7.3.4), reactor maintenance and repair (Section 7.3.3) and concepts involving the Shuttle as a nuclear system transportation vehicle (see Volume IV) all substantiate this conclusion. Although reversible means for accomplishing this separation have been considered in previous separable heat exchanger work, permanent separation techniques may allow achieving at least partial enhancement of safety (during reactor disposal) without attendant penalties in system performance. Studies should be performed which would indicate approaches to providing reactor separation techniques to maximize nuclear safety while minimizing system performance penalties.

8.4.2 APPROACH

Operational requirements for a separable heat exchanger would be established (e.g., operating temperature levels, allowable temperature differentials, quantity of heat to be transferred). Candidate concepts would then be investigated to select most promising concepts. Concepts include use of heat pipes and low melt temperature heat transfer metals.

These steps would be followed by an analysis and conceptual design of a candidate separable heat exchanger using heat transfer principles previously investigated. This technology program would lead to the development of specifications and predicted performance characteristics. Special studies related to the use of a separable heat exchanger would be instigated such as materials investigations and a conceptual design of a self-sealing quick disconnect for NaK service.

8.5 REACTOR PROTECTION TECHNOLOGY

8.5.1 OBJECTIVES/REQUIREMENTS

The discussions in Section 6, 7 and In Volume III, Part 2 of this study indicate the importance of a reliable reactor protection system. The adequacy of a LiH shield as presently envisioned for use with the ZrH reactor is in question. A technology program should be initiated prior to establishing a firm reactor shield design which addresses the following:

1. Investigations to provide assurance that the reactor protection system will:
   a. Perform as a nuclear radiation shield
   b. Be capable of resisting penetration and/or loss of shielding effectiveness in orbit.
   c. Dissipate reactor waste heat without degradation of shield material.
   d. Provide protection through aerodynamic reentry and subsequent earth impact.
2. Determine effects on reliability and performance due to:
   a. Long term radiation environment

b. Long term high temperature environment

c. Irregular surfaces

8.5.2 APPROACH

Requirements for a reactor protection system would be established. Preliminary design concepts would then be developed based on a reference reactor power module program/mission(s). Trade-off studies would then be conducted, important parameters being shielding effectiveness, reentry capability, mass, manufacturing capability, reliability, cost, etc. Selected materials and configuration concepts would be evaluated and necessary test programs conducted. The ability of the material and material matrix to meet the requirements previously established would be ascertained, i.e., radiation shield, reentry burn up, earth impact.

The optimum material would be selected and preliminary design concepts would be developed. Full scale tests should be performed prior to commitment to a flight program.

8.6 BLAST AND FRAGMENTATION PROTECTION SCHEMES AND ESTIMATION MODELS

8.6.1 OBJECTIVES/REQUIREMENTS

The high energy fragments resulting from exploding tanks are of major concern for the proper design of nuclear hardware, as well as spacecraft equipment. The source of this fragmentation includes booster propellant tanks as well as storage tanks aboard the spacecraft. However, very little information or data is currently available to characterize the fragments with regard to size, shape and velocity. The purpose of this proposed program is to develop analytical models, supported by an extensive test program, for the prediction of tankage fragmentation as well as the study of shielding materials and methods of protection.

8.6.2 APPROACH

The test portion of the program would in general consist of two phases:

1. To determine the fragmentation distribution in a typical tankage field and to access the vulnerability of other tankage systems in the vicinity, and

2. To determine the characteristics of shielding materials, and methods for protecting tankage and nuclear heat sources in the vicinity of the initial explosion. It is anticipated that a typical test would consist of scaled tankage arranged in a representative manner and surrounded by a barrier of selected geometry and material (such as wood) which would capture the fragments and thus yield information on velocity, mass and geometric distribution. A selected shielding system would then be inserted into the test arrangement and the test would be repeated to evaluate the shielding design. Analytical techniques would be developed or extended in parallel with the test program and correlation between test and analytical results would be developed. The output of the effort would be improved shielding materials and designs, and analytical tools for use in designing future systems.

8.7 REACTOR PERMANENT SHUTDOWN

8.7.1 OBJECTIVES/REQUIREMENTS

Discussion in Section 7.3 and in Volumes III and IV substantiate the need for a permanent reactor shutdown system. Such a system would significantly reduce the risks due to a reactor impact on the earth's surface or in shallow water areas. Therefore a program should be initiated to investigate the techniques, feasibility and merits of a positive and permanent reactor shutdown system to preclude reactor criticality and excursion accidents during disposal and on earth impact.

8.7.2 APPROACH

Requirements of the system would be defined. Preliminary design concepts would be formulated, i.e., pre-poisoning of fuel, control drum lock-out devices, poison injection, release of hydrogen moderator, etc. Trade-off studies would then be performed addressing such parameters as effect on reliability, cost, performance penalties, etc. Candidate techniques would be evaluated and tested prior to commitment to full scale qual and flight reactor hardware.

8.8 NUCLEAR DEBRIS IN-ORBIT

8.8.1 OBJECTIVES/REQUIREMENTS

The analyses of Section 6.3.2 indicated the projected severity of accidents which result in the dispersion of radioactive debris. To allow an assessment of the severity of these accidents, a simple model of the events (e.g., destructive reactor excursion, NaK leaks, etc) was postulated. The model is possibly conservative, but indicates that severe effects (over-exposure) would be experienced by the crew in the event of a destructive reactor excursion and that very little time is available to implement contingency procedures.

In order to establish definitive procedures and design requirements to cope with this hazard of radioactive debris a more accurate model of the immediate and long term distribution of the possible debris is required. Not only is this a necessity in establishing the responsive action to be taken on the orbital vehicle, but also in defining emergency space rescue operations.

8.8.2 APPROACH

An analytical study would be supplemented by a test program, possibly based on SNAPTRAN air burst tests, to obtain a reasonable estimate of debris fragment size, velocity and characteristics representative of an orbital excursion. Tests may also be required to determine characteristics of released radioactive gases and liquid metals. This data would be used in determining quantities, types and stay times of debris around the Base. Total integration doses to the Base and crew would be determined and preventative measures and contingency plans formulated.

8.9 IN-ORBIT DECONTAMINATION TECHNIQUES

8.9.1 OBJECTIVES/REQUIREMENTS

As discussed in Section 7.3.2, conventional means of dealing with radioactive contamination in a gravity environment are not generally applicable to zero-g application. It will, therefore, be necessary to develop in-orbit decontamination techniques particularly for laboratories and storage areas using isotope tracers and isotope fuel capsules. These techniques should

provide for on-board implementation and consideration should be given to experiments testing these techniques on forthcoming manned space flights.

8.9.2 APPROACH

The candidate isotope systems to be flown and modes of isotope release would be identified.

Decontamination requirements would be established and concepts formulated for zero "g" and artificial "g" application in representative manned earth orbital spacecraft. Simulated tests would be performed on earth with eventual testing of selected concepts proposed for a manned earth orbiting experiment on forthcoming space flights.

8.10 SPACE QUALIFIED RADIATION MONITORING EQUIPMENT

8.10.1 OBJECTIVES/REQUIREMENTS

Section 7.3.1 indicates the elements of an on-board radiological safety program to be implemented by the crew of a Space Base. While the equipment required by this program is available with needed sensitivities for earth-bound application, a majority of the equipment has not been qualified for Space Flight. In addition, the equipment should be specifically designed to accommodate the background radiations associated with the mission. These instruments should be designed to be flexible in function, thus minimizing the inventory of sensors and equipment to be carried.

8.10.2 APPROACH

The radiation monitoring requirements, i.e., sensitivities, quantities, application, etc., would be established. A review of current equipment used in earth and space applications would be made and matched with the program requirements. Commonality of hardware and usage would be stressed. Selected concepts would be evaluated for space application and subsequent space flight qualification would be initiated. New technology requirements would be identified and programs initiated.

8.11 STANDARDIZATION OF SAFETY ANALYSIS TECHNIQUES

8.11.1 OBJECTIVES/REQUIREMENTS

At the present time, there are no firm guidelines to direct the safety analysis study programs (terrestrial safety type) of nuclear power systems. Consequently, the results presented by different contractors are often difficult to compare and usually do not present a tangible measure of safety. Hence, it is difficult to determine the true effectiveness of design changes or modifications. A standardized approach should be developed, which would be used by a contractor as a guide for performing a nuclear safety analysis.

8.11.2 APPROACH

A handbook would be prepared which describes the requirements for a nuclear safety analysis. This handbook would be flexible in that it would allow the contractor to modify analyses and to incorporate new situations into the study wherever appropriate. Formal mechanisms for change would be specified. Guidelines would be given for all phases to aid in the analysis. Where appropriate, these guidelines would include specific models to be used with explanations for their use. These would include, for example, booster fragmentation models, probability models, meteorological models, radiation exposure models, and risk models. Uniform procedures would be specified for the identification and reporting of accidents and imposed risk.

APPENDIX A

RADIATION EXPOSURE LIMITS AND EFFECTS

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APPENDIX A
RADIATION EXPOSURE LIMITS AND EFFECTS

A. 1 INTRODUCTION

This appendix defines and/or tabulates the radiation exposure limits to be used in various mission vulnerability and hazards analyses which can be a part of future manned space missions. The work identified is part of the Radiation Exposure Limits task of the Space Base Nuclear System Safety Study, Contract No. NAS8-26283.

The objective of the task was to develop engineering estimates of the effects of each of the various radiation environments of concern for all segments of a Space Base Mission. The environments of interest include the reactor source, various isotopes and the natural space radiation environment. The effort was divided into the following four major areas: Support Subsystems, Non-Biological Experiment Subsystems, Biological Experiments and Human Considerations. Radiation effects data and safe exposure limits have been developed for each of these four areas. The primary purpose was not to assess the impact of a particular environment on the Space Base Mission but rather to develop the basic effects data by which such mission vulnerability and hazards analyses may be carried out in subsequent Study efforts.

The general approach was to utilize the Space Base system baseline developed for the study (see Section 3. 0) carry out a detailed data search and compilation and to use this data to generate the appropriate radiation effects limits required for subsequent mission analyses. No new basic radiation effects data was generated. The exposure limits were developed from existing experimental data, or where no data was found to exist, on engineering estimates and analytical approximations.

Each of the above areas are discussed separately in the following sections. The results are given in the form of detailed data tables as well as summary charts for each area. Because of the many varied sources of data and information used in the study, special emphasis was placed upon identifying the basis of each particular exposure limit developed. This will be of

great assistance in future considerations of new data in evaluating and updating the exposure thresholds.

Due to the many important modifying factors associated with radiobiological and scientific aspects of the mission, supporting data are included which contain detailed radiation effects data to supplement the summary tables.

A.2 RADIATION EFFECTS ON SPACE BASE SUPPORT SUBSYSTEMS

The radiation damage levels of the various support subsystems and components which comprise a Space Base Program, exclusive of the biological and non-biological experiments payload and crew complement, are presented here. The functional description of the Space Base Program utilized in carrying out this study is that given in the North American Rockwell (NAR) Space Base Definition, DRL No. MSC T-575, and the McDonnell Douglas (MDAC) Space Base Definition DRL No. MSFC-DRL-160. Since much of the system design is preliminary in nature, this initial radiation sensitivity assessment is preliminary in many respects due to the lack of detailed component design data and piece-part and material definition for the majority of components. The results, nonetheless, will be very useful in determining the impact of the presence of nuclear power sources on a Space Base.

Where possible, the present evaluation is based upon experimental radiation effects data. For piece parts and materials for which no data is available, either (1) analytical techniques were utilized to predict the component or material response or (2) radiation effects data for similar piece parts or materials was used. Also, where component design was such that the piece parts and materials to be used in the design were not yet identified, a generic definition of the piece parts or materials usually utilized in such applications was assumed.

A.2.1 RADIATION DAMAGE THRESHOLDS - SPACE BASE SUPPORT SUBSYSTEM COMPONENTS

The radiation damage thresholds for the components within each of the Space Base Support Subsystems were determined for both the NAR and MDAC subsystems identified in Table A-1 for each individual portion of the total mission radiation environment. These environments

consist of the reactor neutron and gamma environments together with the natural trapped electron and proton radiations as well as solar event proton and alpha particles. The level of definition for each component's damage threshold is consistent with the level of the subsystem definition as provided in the NAR & MDAC Space Base Definitions.

Table A-1. System Definition

NAR

- ELECTRICAL POWER (EP)
- ENVIRONMENTAL CONTROL AND LIFE SUPPORT (ECLS)
- INFORMATION (INF)
- GUIDANCE AND CONTROL (G&C)
- PROPULSION AND REACTION CONTROL (P&RC)
- CREW AND HABITALITY (C&H)
- ENVIRONMENTAL PROTECTION (ENV P)
- DOCKING (DOCK)

MDAC

- ELECTRICAL POWER (EP)
- ENVIRONMENTAL CONTROL AND LIFE SUPPORT (ECLS)
- DATA MANAGEMENT (DM)
- COMMUNICATIONS (COM)
- ON BOARD CHECKOUT (OBC)
- STABILIZATION AND ATTITUDE CONTROL (S&AC)
- GUIDANCE AND NAVIGATION (G&N)
- PROPULSION (PROP)
- CREW HABITALITY AND PROTECTION (CH&P)
- MECHANICAL (MECH)

In the majority of cases, the individual subsystems are only defined down to a generic component level. In these instances the components were examined with respect to their particular usage and performance requirements. The typical piece parts and materials which could be employed in each component to accomplish the particular function was then determined. Where reference was made to a specific piece part or material in either the NAR or MDAC definition, the particular item was used in the component defintion.

Damage thresholds for most piece parts and materials were readily established by a direct application of available experimental radiation effects data. When data was lacking, damage thresholds for similar piece parts and materials were assumed. The threshold damage level given here for a particular component is that level of radiation dose where the materials and piece parts which make up the component or subsystem are beginning to experience a significant change in their characteristics. In the actual design of a component, variation in the piece part and material characteristics can be accounted for to a large extent. Thus, the component damage threshold levels will, in general, be higher than for the piece parts and materials that make up the component. However, for this assessment, the typical piece part thresholds were assumed to represent those for the components as well. This, for the most part, would be a conservative assumption.

In those instances where radiation effects data was not available for each individual portion of the mission environment, experimentally determined particle and photon equivalency data was utilized. For materials the primary damage mechanism is due to ionization effects and the radiation equivalency is generally in the form of equal ionization dose values. That is, equal ionization doses from penetrating electrons, protons, gamma photons, etc., generally result in the same level of damage in a particular material. An example of an ionization equivalency relationship for silicon is given in Figure A-1. For semiconductor electronics both bulk (crystal) damage and ionization (surface) damage mechanisms are possible. The bulk damage equivalency, however, is not as straight-forward as ionization equivalencies. Here recourse must be made to experimentally determined equivalency values for a particular class of devices. An example of the bulk damage equivalency relation for silicon transistors is given in Figure A-2 which shows the relative effectiveness of various types of radiations in causing the same level of damage in the devices. Both the bulk damage and ionization relationships are of primary importance in developing the total effects of various concurrent radiation environments.

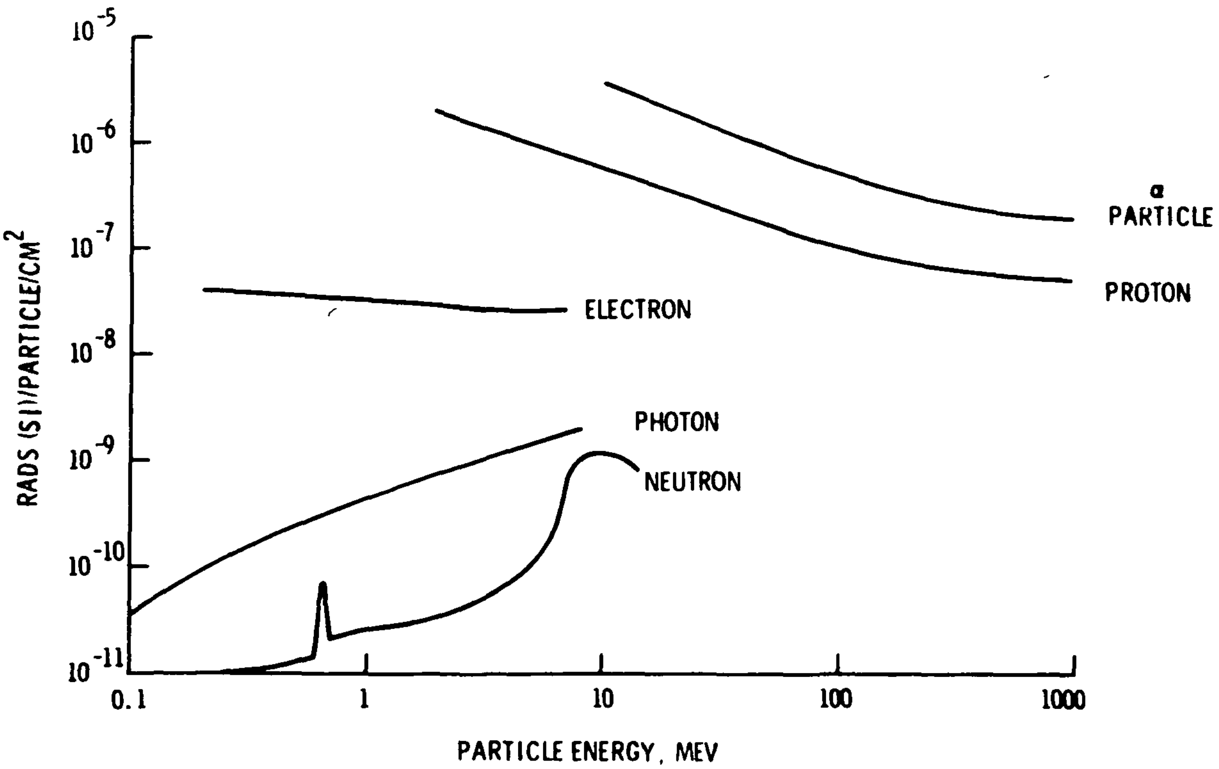

Figure A-1. Unit Flux Ionization Dose in Silicon

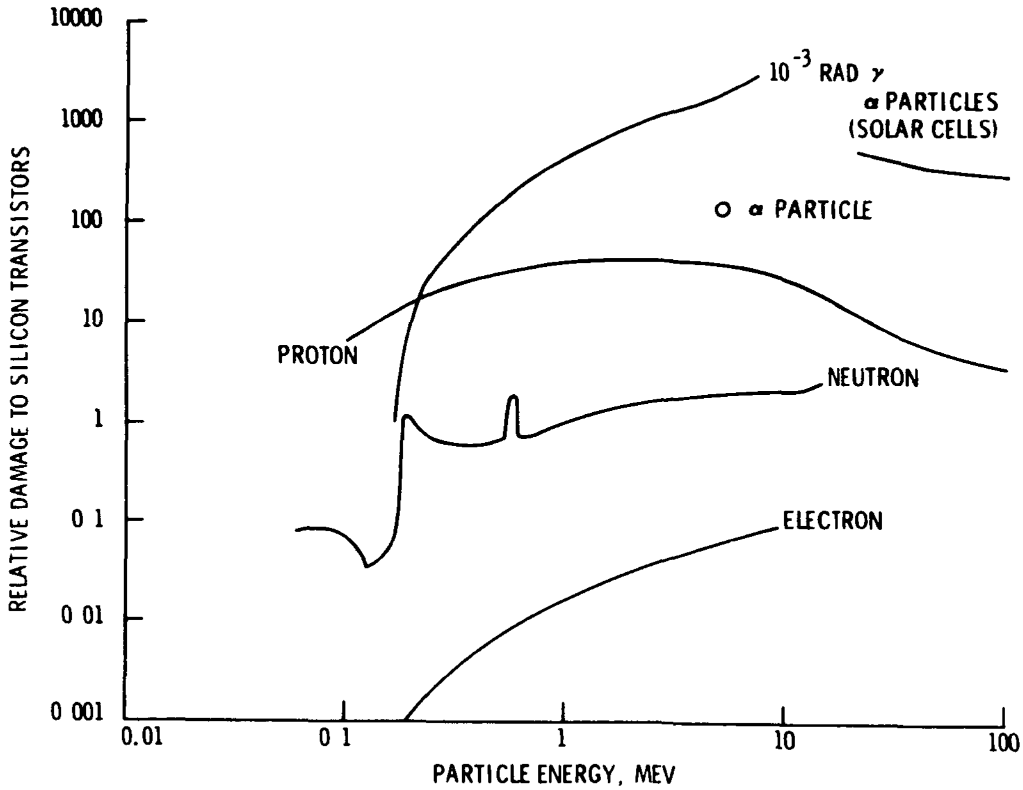

Figure A-2. Relative Bulk Damage Effects in Silicon Transistors (Normalized to 1 Mev Neutrons)

In carrying out the component analysis, a number of assumptions concerning semiconductor and material damage criteria were followed. This was particularly so for the semiconductor electronics devices, which are undoubtedly the most radiation-sensitive devices that make up the subsystems. The radiation damage thresholds for bulk damage and ionization effects in transistors is based upon that radiation dose which will cause at least 5 percent reduction in current gain at ~ 300°K (25°C).

In general, those materials which are performing noncritical functions are also the most radiation-resistant. Therefore, a large number of materials can be eliminated from the list of sensitive materials by a cursory investigation of each component having specific reference to structural materials (i.e., component housings, transistor cans, etc.), since they are of a generally radiation-resistant metallic composition. Correspondingly, those materials utilized in the highly critical functions on a spacecraft also happen to be the most sensitive to radiation damage. Aside from the highly critical semiconductor devices, most of the

other critical functions are performed by organic materials, generally in mechanical applications and the relatively more radiation resistant inorganic materials in optical applications. Organic material radiation damage thresholds have been found to differ at various temperatures as well as when the materials are immersed in different liquids. In addition, damage thresholds have also been found to differ for a variety of irradiation atmospheres, i.e., vacuum, air, or other gas. A complete and accurate definition of these thresholds is desirable because of the possible combined environments which may be imposed on these materials in a Space Base. However, damage threshold definition of this nature was not available. Since vacuum, temperature, and immersion media tend to increase the radiation stability of most organic materials over that for air, and since a large portion of a Space Base is provided with a "shirtsleeve" environment (air), damage thresholds in air were assumed herein for the organic materials defined in each component.

Using the above techniques, component radiation damage thresholds were determined for each of the identifiable Space Base components. The detailed results of these radiation sensitivity analyses are given in Table A-2. The generic identification for each component is given as well as its respective subsystem location in both the NAR and MDAC configurations. The typical piece parts and materials which could be used in the fabrication of each component and which would probably limit component performance in a radiation environment are also identified. Radiation damage levels for each of these limiting items are given for the various radiation environments of concern. The alpha-numeric information enclosed in parentheses following each radiation dose entry in the Table refer to specific reference from which the radiation damage level data was obtained or to specific analytical techniques which were used to determine the particular damage level.

A.2 RADIATION DAMAGE LEVELS - SPACE BASE SUPPORT SUBSYSTEMS

The component radiation damage levels given in the previous section relate specifically to those levels which are indicative of component damage threshold. However, to completely evaluate the significance of the various hazards which could occur with a nuclear powered Space Base System, the various degrees of damage beyond threshold and their corresponding radiation levels must be established. Damage characteristics such as these can be developed

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems

SPACE BASE COMPONENT				DAMAGE THRESHOLD						
	SUBSYSTEM LOCATION			BULK DAMAGE EFFECTS*					IONIZATION EFFECTS	
COMPONENT	NAR	MDAC	TYPICAL PART OR MATERIAL	1 MEV N/CM²	RADS γ	1 MEV E/CM²	10 MEV P/CM²	MEV α/CM²	RADS	REMARKS
POWER SYSTEM	EP	EP	REACTOR	A	A	A	A	A	A	
			SHIELD	A	A	A	A	A	A	
			BRAYTON POWER CONVERSION UNIT	A	A	A	A	A	A	SNAP-8 EQUIPMENT DESIGNED TO SURVIVE 10^7 R & 5 x 10^{12} N/CM² (1)
REACTOR INSTRUMENTATION	EP	EP	THERMISTORS & THERMOCOUPLES	$>10^{14}$ (-)	B	B	B	B	$>10^7$ (-)	
RADIATOR PUMPS - LUBRICANTS	EP	EP	PBS + MoS_2 + B_2O_3	$>10^{16}$ (3)	B	B	B	B	$>10^9$ (3)	
			CaF_2 + OXIDE FRIT	$>10^{16}$ (3)	B	B	B	B	$>10^9$ (3)	
			MoS_2 + GRAPHITE + SODIUM SILICATE	$>10^{16}$ (3)	B	B	B	B	$>10^9$ (3)	
			VITROLUBE	$\approx 10^{16}$ (4)	B	B	B	B	$\approx 10^9$ (4)	
			MLF-5	$\approx 10^{16}$ (4)	B	B	B	B	$\approx 10^9$ (4)	
			ALMASOL SFD-810	$\approx 10^{16}$ (4)	B	B	B	B	$\approx 10^9$ (4)	
			SURF-KOTE M1284	$>10^{16}$ (4)	B	B	B	B	$>10^9$ (4)	
PARASITIC LOAD										
LOAD RESISTORS	EP	EP	ORGANIC MATERIALS	10^{13} (5, 6)	B	B	B	B	10^6 (5, 6)	
RELAY CONTROL		EP	COIL INSULATION	10^{14} (6)	B	B	B	B	10^7 (6)	
SCR CONTROL	EP		MEDIUM-HIGH CURRENT SCR	10^{11}-10^{12}(7)	2 x 10^5-2 x 10^6 (C)	6x10^{12}-6x10^{13}(C)	10^{10}-10^{11}(C)	7x10^8-7x10^9(C)	10^3-10^4(7)	
ELECTRICAL POWER DISTRIBUTION HARNESS	EP	EP	TEFLON	10^{13} (5)	B	B	B	B	10^4-10^6 (6, 9)	
			IRRADIATED POLYOLEFIN	10^{13}-10^{16} (D)	B	B	B	B	$>10^7$ (9)	
			KAPTON	10^{13}-10^{16} (D)	B	B	B	B	$>10^8$ (9)	
			POLYVINYL CHLORIDE	10^{13}-10^{16} (D)	B	B	B	B	10^7 (9)	
			POLYETHYLENE	4x10^{15} (57)	B	B	B	B	10^7 (8)	
			SILICONE RUBBER	3x10^{14} (57)	B	B	B	B	10^6 (8)	
			POLYIMIDE	$>10^{16}$ (8)	B	B	B	B	$>10^8$ (8)	
POWER REGULATORS CONVERTERS & CIRCUIT BREAKERS	EP	EP	LOW FREQUENCY POWER TRANSISTORS	10^{10}-10^{11} (7, 10)	2x10^4-2x10^5(C)	6x10^{11}-6x10^{12}(C)	10^9-10^{10}(C)	7x10^7-7x10^8(C)	10^3-10^4(7, 10)	SNAP-8 EQUIPMENT DESIGNED TO SURVIVE 10^6 R & 10^{11} N/CM² (11)
POWER CONTROL ELECTRONICS	EP	EP	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7, 10)	2x10^5-2x10^6(C)	6x10^{12}-6x10^{13}(C)	10^{10}-10^{11}(C)	7x10^8-7x10^9(C)	10^3 10^4(7, 10)	
BACK-UP POWER SYSTEM										
SOLAR ARRAY	EP	EP	10 OHM-CM N/P SOLAR CELLS	10^{10}(7, 10)	10^5(7, 10)	2x10^{13}(12)	2x10^{10}(12)	$\approx$2x10^9(E)	F	
			CORNING 7940 COVER GLASS	$>10^{13}$ (C)	B	B	B	B	>9x10^7(13)	
NI-CD BATTERY	EP	EP	SEPARATOR PLATE MATERIAL	$>10^{13}$(14, 15)	B	B	B	B	$>10^6$(14, 15)	
FUEL CELL		EP	ION EXCHANGE MEMBRANE, SEALS, ETC	$>10^{13}$(D)	B	B	B	B	$>10^6$(D)	
HEAT REJECTION LOOP										
HEAT EXCHANGER	EP		DC200 COOLANT	3x10^{13}(D)	B	B	B	B	$\approx 10^5$(61, 62)	
		EP	NAK COOLANT	$>10^{16}$(D)	B	B	B	B	$>10^{10}$(D)	
RADIATOR THERMAL COATING			IRON TITANATE	>5x10^{13} (66)	B	B	B	B	$>10^4$ (66)	
			Z93	10^{14} (16)	B	B	B	B	$\approx$ 3x10^7(16)	
REACTOR ORBIT DISPOSAL										
PROPELLANT	EP	EP	HYDRAZENE	$>10^{13}$(D)	B	B	B	B	10^6(17)	
O RINGS ETC	EP	EP	NYLON	2x10^{14}(57)	B	B	B	B	10^7(5)	
			CHLOROPRENE	$>10^{13}$(D)	B	B	B	B	10^7(5)	
REACTOR OCEAN DISPOSAL										
PROPELLANT	EP		HYDRAZENE	$>10^{13}$(D)	B	B	B	B	10^6(17)	
ELECTRONICS	EP		MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(18)	2x10^5-2x10^6(C)	6x10^{12}-6x10^{13}(C)	10^{10}-10^{11}(C)	7x10^8-7x10^9(C)	10^4-10^6(18)	ELECTRONICS UNACTIVATED UNTIL DISPOSAL REQUIREMENT
MATERIALS	EP		ORGANIC MATERIALS	10^{13}-10^{14}(18)	B	B	B	B	10^5-10^6 (18)	

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems (Cont'd)

SPACE BASE COMPONENT			TYPICAL PART OR MATERIAL	DAMAGE THRESHOLD						REMARKS
	SUBSYSTEM LOCATION			BULK DAMAGE EFFECTS*					IONIZATION EFFECTS	
COMPONENT	MAR	MDAC		1 MEV N/CM2	RADS	2 MEV E CM2	40 MEV P CM2	[illegible] MEV [illegible] CM2	RADS	
O_2 RECOVERY										
SABATIER REACTOR	ECLS	ECLS	NICKEL CATALYST	$>10^{16(D)}$	B	B	B	B	$>10^{10(D)}$	
			ORGANIC SEALS ETC	10^{13}-$10^{16(D)}$	B	B	B	B	10^{4}-$10^{6(19)}$	PRESSURE
H_2O ELECTROLYSIS	ECLS	ECLS	ORGANIC MEMBRANE	10^{14}-$10^{16(6,57)}$	B	B	B	B	$10^{[illegible]}$-$10^{6(6,57)}$	SLIGHT PRESSURE
HUMIDITY CONTROL - CONDENSING HEAT EXCHANGER	ECLS	ECLS	CELLULOSE WICK MATERIAL	10^{14}-$10^{16(6,57)}$	B	B	B	B	$10^{[illegible]}$-$10^{6(6,57)}$	SLIGHT PRESSURE
WASH WATER RECOVERY - REVERSE OSMOSIS	ECLS	ECLS	CELLULOSE ACETATE MATERIAL	8×10^{14}-$6\times10^{15(57)}$	B	B	B	B	[illegible]$\times10^{5}$-$8\times10^{(57)}$	HIGH PRESSURE
			ORGANIC SEALS ETC	10^{13}-$10^{16(19)}$	B	B	B	B	10^{4}-$10^{6(19)}$	HIGH PRESSURE
URINE WATER RECOVERY - VAPOR DIFFUSION/ COMPRESSION	ECLS	ECLS	CELLULOSE ACETATE TYPE MEMBRANE	8×10^{14}-$6\times10^{15(57)}$	B	B	B	B	[illegible]$\times10^{5}$-$3\times10^{6(57)}$	VACUUM
			ORGANIC SEALS ETC	10^{13}-$10^{16(19)}$	B	B	B	B	10^{4}-$10^{6(19)}$	VACUUM
WASTE MANAGEMENT SYSTEM	ECLS	ECLS	ORGANIC DIAPHRAGM	10^{14}-$10^{16(6,57)}$	B	B	B	B	10^{5}-$10^{6(6,57)}$	PRESSURE
			ORGANIC SEALS ETC	10^{13}-$10^{16(19)}$	B	B	B	B	10^{4}-$10^{6(19)}$	PRESSURE
ATMOSPHERE TEMPERATURE CONTROL										
FANS	ECLS	ECSL	LUBRICANTS	$10^{16(3,4)}$	B	B	B	B	$10^{9(3,4)}$	
			MOTOR INSULATION	$10^{14(6)}$	B	B	B	B	$10^{7(6)}$	
HEAT EXCHANGER	ECLS	ECLS	ORGANIC SEALS ETC	10^{13}-$10^{16(19)}$	B	B	B	B	10^{4}-$10^{6(19)}$	
TRACE CONTAMINANT CONTROL - CATALYTIC BURNER	ECLS	ECLS	NOBLE METAL CATALYST	$>10^{16(D)}$	B	B	B	B	$>10^{10(D)}$	
			ORGANIC SEALS ETC	10^{13}-$10^{16(19)}$	B	B	B	B	10^{4}-$10^{6(19)}$	SLIGHT PRESSURE
			REGENERABLE CHARCOAL	$>10^{16(D)}$	B	B	B	B	$10^{10(D)}$	
CO_2 CONTROL										
STEAM DESORBED RESIN		ECLS	ORGANIC MATERIAL (AMINE)	10^{14}-$10^{16(D)}$	B	B	B	B	$10^{[illegible]}$-$10^{6(D)}$	PRESSURE & VACUUM
MEMBRANE DIFFUSION	ECLS		SILICON RUBBER TYPE MEMBRANE	$3\times10^{14(57)}$	B	B	B	B	$10^{6(6)}$	PRESSURE
BACTERIA CONTROL - FILTERS	ECLS	ECLS	FIBERGLASS FILTER	10^{14}-$10^{16(D)}$	B	B	B	B	$\sim10^{6}$-$10^{7([illegible])}$	
H2O & ATMOSPHERE STORAGE TANKS - SEALS ETC	ECLS	ECLS	ORGANIC MATERIALS	10^{13}-$10^{16(D)}$	B	B	B	B	10^{4}-$10^{6(19)}$	
PUMPS, VALVES ETC - O RINGS, SEALS ETC	ECLS	ECLS	TEFLON	$10^{13([illegible])}$	B	B	B	B	[illegible]	
			VITON	10^{13}-$10^{16(D)}$	B	B	B	B	[illegible]	

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems (Cont'd)

SPACE BASE COMPONENT				DAMAGE THRESHOLD						
	SUBSYSTEM LOCATION			BULK DAMAGE EFFECTS*					IONIZATION EFFECTS	
COMPONENT	NAR	MDAC	TYPICAL PART OR MATERIAL	1 MEV N/CM^2	RADS γ	1 MEV E/CM^2	30 MEV P/CM^2	5 MEV α/CM^2	RADS	REMARKS
THERMAL CONTROL										
FLUID	ECLS	ECLS	FREON 21	10^{11}(D)	B	B	B	B	10^{7}(15)	DATA FOR FREON & FREON 11
COATING	ENV P	ECLS	WHITE PAINT	10^{14}(16)	B	B	B	B	≈ 5×10^{7}(16)	
CONTROL ELECTRONICS	ECLS	ECLS	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7 10)	2×10^{5}-2×10^{6}(C)	6×10^{12}-6×10^{13}(C)	10^{10}-10^{11}(C)	7×10^{8}-7×10^{9}(C)	10^{3}-10^{4}(7 10)	
DATA PROCESSING EQUIPMENT	INF	DM	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	2×10^{6}-2×10^{7}(C)	6×10^{13}-6×10^{14}(C)	10^{11}-10^{12}(C)	7×10^{9}-7×10^{10}(C)	10^{3}-10^{4}(7 10)	
			INTEGRATED CIRCUITS	10^{12}-10^{13}(20 21)	2×10^{6}-2×10^{7}(C)	6×10^{13}-6×10^{14}(C)	10^{11}-10^{12}(C)	7×10^{9}-7×10^{10}(C)	10^{3}-10^{4}(7 10)	
			MOSFETS	$>10^{13}$(22)	B	B	B	B	10^{3}-10^{4}(23)	
			JFETS	10^{13}-10^{14}(24)	B	B	B	B	10^{3}-10^{4}(25)	IONIZATION DAMAGE TO LEAKAGE CURRENT DEVICE ON CHARACTERISTICS NEGLIGABLY EFFECTED UP TO 10^{9} R (25)
CO-AXIAL DATA CABLE	INF	DM	TEFLON DIELECTRIC (TFE)	10^{13}(5)	B	B	B	B	10^{4}-10^{5}(6 8)	
			POLYETHYLENE DIELECTRIC	4×10^{15}(57)	B	B	B	B	10^{7}(8)	
TAPE RECORDER										
MAGNETIC TAPE	INF	DM/CH&P	MYLAR TAPE	10^{16}(57)	B	B	B	B	5×10^{6}(63)	
ELECTRONICS	INF	DM/CH&P	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7 10)	2×10^{5}-2×10^{6}(C)	6×10^{12}-6×10^{13}(C)	10^{10}-10^{11}(C)	7×10^{8}-7×10^{9}(C)	10^{3}-10^{4}(7 10)	
CLOCK										
TIMING ELEMENT	INF	DM	CRYSTAL (NON ELECTRICALLY SWEPT)	10^{13}(26 27 28)	B	B	B	B	10^{3}-10^{4}(26 27 28)	
ELECTRONICS	INF	DM	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	2×10^{6}-2×10^{7}(C)	6×10^{13}-6×10^{14}(C)	10^{11}-10^{12}(C)	7×10^{9}-7×10^{10}(C)	10^{3}-10^{4}(7 10)	
DATA DISPLAY SYSTEM										
PERMANENT RECORD	INF	DM/CH&P	FILM (EXCLUDING POLAROID)	6×10^{6}-4×10^{9}(29)	B	B	B	B	1-100 (30 to 35)	POLAROID ASA 3000 SENSITIVE AT 0 1R (33)
NON PERMANENT RECORD	INF	DM	TV TUBE	10^{13}(15, 36)	B	B	B	B	10^{5}(15 36)	
			CRT	10^{13}(D)	B	B	B	B	10^{5}(D)	
			LED							
			Ga As (EPITAXIAL)	2×10^{9}(C)	3×10^{3}(C)	10^{11}(37)	2×10^{8}(C)	10^{7}(C)	F	INCLUDES DAMAGE TO LENS
			Ga As (DIFFUSED)	3×10^{10}(C)	6×10^{4}(C)	2×10^{12}(37)	3×10^{9}(C)	2×10^{8}(C)	F	INCLUDES DAMAGE TO LENS
			Ga As P	3×10^{10}(C)	6×10^{4}(C)	2×10^{12}(37)	3×10^{9}(C)	2×10^{8}(C)	F	INCLUDES DAMAGE TO LENS
			Ga P	8×10^{9}(C)	10^{4}(C)	5×10^{11}(37)	8×10^{8}(C)	6×10^{7}(C)	F	INCLUDES DAMAGE TO LENS
			Si C	3×10^{10}(C)	6×10^{4}(C)	2×10^{12}(37)	3×10^{9}(C)	2×10^{8}(C)	F	INCLUDES DAMAGE TO LENS
HOLOGRAPHIC MEMORY		DM	SEMICONDUCTOR LIGHT SOURCE	2×10^{9}-2×10^{11}(C)	3×10^{3}-3×10^{5}(C)	10^{11}-10^{13}(37)	2×10^{8}-2×10^{10}(C)	10^{7}-10^{9}(C)	F	INCLUDES DAMAGE TO LENS
			HIGH PURITY LENSES	$>10^{12}$(38)	B	B	B	B	10^{5}(38)	
ANTENNAE										
THERMAL CONTROL COATING	INF	COM	WHITE PAINT	10^{14}(16)	B	B	B	B	≈ 5×10^{7}(16)	
RF DIELECTRIC	INF	COM	POLYETHYLENE	4×10^{15}(57)	B	B	B	B	10^{7}(8)	
			TEFLON (TFE)	10^{13}(5)	B	B	B	B	10^{4}-10^{5}(6 8)	

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems (Cont'd)

SPACE BASE COMPONENT			TYPICAL PART OR MATERIAL	DAMAGE THRESHOLD						REMARKS
	SUBSYSTEM LOCATION			BULK DAMAGE EFFECTS*					IONIZATION EFFECTS	
COMPONENT	NAR	MDAC		1 MEV N CM²	RADS	1 MEV E CM²	MEV P CM²	MEV CM²	RADS	
CO-AXIAL TRANSMISSION LINES WAVEGUIDES ETC	INF	COM	POLYETHYLENE DIELECTRIC	$4x10^{15}$(?)	B	B	B	B	10^{7}(?)	
			TEFLON DIELECTRIC (TFE)	10^{15}(5)	B	B	B	B	10^{4}-10^{5}(6 ?)	
TRANSMITTERS & RECEIVERS	INF	COM	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$ $7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
			Ga As GUNN DIODES	10^{13}(39 40)	$2x10^{7}$(C)	$6x10^{14}$(C)	10^{12}(C)	$7x10^{10}$(C)	10^{3} 10^{4}(G)	
			TRAPATT OSCILLATORS	10^{14}(41)	$2x10^{8}$(C)	$6x10^{15}$(C)	10^{13}(C)	$7x10^{11}$(C)	10^{3} 10^{4}(G)	
			IMPATT OSCILLATORS	10^{14}(42)	$2x10^{8}$(C)	$6x10^{15}$(C)	10^{13}(C)	$7x10^{11}$(C)	10^{3}-10^{4}(G)	
			TUNNEL DIODES	$>10^{13}$(12)	$>2x10^{7}$(C)	$>6x10^{14}$(C)	$>10^{12}$(C)	$>7x10^{10}$(C)	10^{3} 10^{4}(G)	
			TWT	10^{13}(5 12)	B	B	B	B	10^{6}(5 12)	
AMPLIFIERS RF ELECTRONICS ETC	INF	COM	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
DIAGNOSTIC COMPUTER	INF	OBC	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
			INTEGRATED CIRCUITS	10^{12}-10^{13}(20 21)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
			MOSFETS	$>10^{13}$(22)	B	B	B	B	10^{3}-10^{4}(23)	
			JFETS	10^{13}-10^{14}(24)	B	B	B	B	10^{3}-10^{4}(25)	
DIAGNOSTIC CONTROL ELECTRONICS	INF	OBC	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7, 10)	$2x10^{5}$-$2x10^{6}$(C)	$6x10^{12}$-$6x10^{13}$(C)	10^{10}-10^{11}(C)	$7x10^{8}$-$7x10^{9}$(C)	10^{3}-10^{4}(7 10)	
DIAGNOSTIC DISPLAY SYSTEM	INF	OBC	SEMICONDUCTOR DISPLAY DEVICES	$2x10^{9}$-$2x10^{10}$(C)	$3x10^{3}$-$3x10^{4}$(C)	10^{11}-10^{12}(37)	$2x10^{8}$-$2x10^{9}$(C)	10^{7}-10^{8}(C)	F	
			CRT & TV TUBE	10^{13}(15, 36)	B	B	B	B	10^{9}(15 36)	
STAR SENSOR & LANDMARK TRACKER										
DETECTOR	G&C	S&AC/G&N	PHOTO TUBE	$>10^{12}$(15 43)	B	B	B	B	10^{5}(15 43)	
SUN SENSOR	G&C	S&AC/G&N	PHOTO TRANSISTOR	10^{10} 10^{11}(7)	$2x10^{4}$-$2x10^{5}$(C)	$6x10^{11}$-$6x10^{12}$(C)	10^{9}-10^{10}(C)	$7x10^{7}$-$7x10^{8}$(C)	1-10^{3} R/HR(44) 10^{3}-10^{4}(7 10)	DYNAMIC INTERFERENCE
			CDS PHOTO-RESISTIVE DEVICE	10^{13}(7)	$2x10^{7}$-$2x10^{8}$(C)	$6x10^{14}$-$6x10^{15}$(C)	10^{12} 10^{13}(C)	$7x10^{10}$-$7x10^{11}$(C)	$\approx 10^{5}$(7)	
ELECTRONICS	G&C	S&AC/G&N	HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
HORIZON SENSOR										
DETECTOR	G&C	S&AC/G&N	INFRARED SENSING ELEMENT	10^{12}-10^{13}(14, 45)	10^{5}-10^{6}(45)	$6x10^{13}$ $6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	F	
WINDOW	G&C	S&AC/G&N	SILICON OR GERMANIUM	10^{15}(45, 46)	10^{8}(45 46)	$3x10^{15}$ (I)	$4x10^{14}$ (I)	$5x10^{12}$ (I)	10^{8} (45 46)	
ELECTRONICS	G&C	S&AC/G&N	HIGH FREQUENCY TRANSISTORS	10^{12}- 10^{13}(7 10)	$2x10^{6}$ $2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$ $7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
CONTROL MOMENT GYRO	G&C	S&AC	ORGANIC MATERIALS	10^{14}(47)	B	B	B	B	10^{6} 10^{7}(47)	
ELECTROSTATIC GYRO		S&AC/G&N	ORGANIC SEALS ETC	10^{13} 10^{16}(13)	B	B	B	B	10^{6} 10^{7}(13)	

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems (Cont'd)

SPACE BASE COMPONENT: COMPONENT	SUBSYSTEM LOCATION: NAR	SUBSYSTEM LOCATION: MDAC	TYPICAL PART OR MATERIAL	DAMAGE THRESHOLD — BULK DAMAGE EFFECTS*: 1 MEV N/CM²	RADS γ	1 MEV E/CM²	30 MEV P/CM²	5 MEV α/CM²	IONIZATION EFFECTS: RADS	REMARKS
STRAP DOWN GYROS	G&C		ORGANIC MATERIALS	10^{13}(2)	B	B	B	B	10^{6} 10^{7}(2)	
ACCELEROMETER & TACHOMETER	G&C	S&AC	ORGANIC MATERIALS	10^{13}(2)	B	B	B	B	10^{4}-10^{6}(2)	
FRICTION LOSS COMPENSATION MOTOR	G&C		ORGANIC MATERIALS	10^{13}(5)	B	B	B	B	10^{4}-10^{6}(5)	
			MOTOR INSULATION	10^{14}(6)	B	B	B	B	10^{7}(6)	
LASER COMPONENTS										
LASER DEVICE	G&C/ DOCK	S&AC/G&N/ MECH	YAG Nd	$>10^{13}$ (D)	B	B	B	B	$\approx 10^{3}$ 10^{4}(37) (10^{11} 2 5 MEV E CM²)	ROOM TEMPERATURE ANNEALING UNDER OPERATING CONDITIONS OCCURS $\approx 10^{6}$ SEC AFTER 10^{14} 2 5 MEV E CM² & $\approx 10^{4}$ SEC AFTER $5x10^{9}$ 32 MEV P CM RECOVERY OCCURS (37 48)
			Ga As	$2x10^{12}$ (C)	$3x10^{6}$ (C)	$\approx 10^{14}$ (37) (2 5 MEV ELECTRONS)	$2x10^{11}$(C)	10^{10} (C)	F	ROOM TEMPERATURE ANNEALING UNDER OPERATING CONDITIONS OCCURS RECOVERY AFTER 10^{6} SEC AFTER $5x10^{4}$ 2 5 MEV E/CM² (37)
			RUBY	$>10^{13}$ (D)	B	B	B	B	10^{3}-10^{4}(49)	ROOM TEMPERATURE ANNEALING UNDER OPERATING CONDITIONS OCCURS (49)
PERIPHERAL EQUIPMENT	G&C/ DOCK	S&AC/G&N/ MECH	FLASH LAMP, MIRRORS, METALLIC COUPLING REFLECTORS	$>10^{13}$(D)	B	B	B	B	$>10^{6}$(49)	
			HIGH PURITY LENSES	$>10^{12}$(38)	B	B	B	B	10^{8}(38)	
CONTROL ELECTRONICS	G&C/ DOCK	S&AC/G&N/ MECH	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7 10)	$2x10^{5}$-$2x10^{6}$(C)	$6x10^{12}$-$6x10^{13}$(C)	10^{10}-10^{11}(C)	$7x10^{8}$-$7x10^{9}$(C)	10^{3}-10^{4}(7, 10)	
TELESCOPE/ SEXTANT	G&C		HIGH QUALITY OPTICAL MATERIALS	$>10^{12}$(38)	B	B	B	B	10^{6}-10^{8}(38, 50)	
REACTION JETS	G&C	S&AC/G&N	ORGANIC SEALS, SEATS, ETC	10^{13}-10^{16}(D)	B	B	B	B	10^{4}-10^{6}(19)	
CONTROL ELECTRONICS	G&C	S&AC/G&N	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7, 10)	$2x10^{5}$-$2x10^{6}$(C)	$6x10^{12}$-$6x10^{13}$(C)	10^{10}-10^{11}(C)	$7x10^{8}$-$7x10^{9}$(C)	10^{3}-10^{4}(7, 10)	
RANGING & RENDEZVOUS RADAR	G&C	G&N	RF DEVICES & HIGH FREQUENCY TRANSISTORS	10^{12}-10^{13}(7 10)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$-$7x10^{10}$(C)	10^{3}-10^{4}(7 10)	
GUIDANCE COMPUTER (DIGITAL & ANALOG)	G&C	S&AC/G&N	ANALOG AMPLIFIERS	$\approx 10^{12}$(51 52)	$2x10^{6}$(C)	$6x10^{13}$(C)	10^{11}(C)	$7x10^{9}$(C)	10^{3}-10^{4}(7 10)	
			SEMICONDUCTOR DIGITAL CIRCUITS	10^{12} 10^{13} (7 10 20 21 22 24)	$2x10^{6}$-$2x10^{7}$(C)	$6x10^{13}$-$6x10^{14}$(C)	10^{11}-10^{12}(C)	$7x10^{9}$ $7x10^{10}$(C)	10^{3}-10^{4} (7 10 23 25)	
RESISTOJET PROPULSION SYSTEM										
PROPELLANT	P&RC	PROP	CH_4+CO_2+H_2&H_2O	$>10^{13}$(D)	B	B	B	B	$\approx 5x10^{5}$(3 54)	
O RINGS ETC	P&RC	PROP	VITON B	$>10^{13}$(D)	B	B	B	B	$\approx 10^{6}$(5)	
PUMPS ETC	P&RC	PROP	ORGANIC SEALS ETC	10^{13}-10^{16}(D)	B	B	B	B	10^{4} 10^{6}(19)	

Table A-2. Radiation Damage Thresholds of the Components in the Space Base Support Subsystems (Cont'd)

SPACE BASE COMPONENT				DAMAGE THRESHOLD						
	SUBSYSTEM LOCATION			BULK DAMAGE EFFECTS*					IONIZATION EFFECTS	
COMPONENT	NAR	MDAC	TYPICAL PART OR MATERIAL	1 MEV N/CM²	RADS γ	1 MEV E/CM²	30 MEV P/CM²	5 MEV α/CM²	RADS	REMARKS
CHEMICAL PROPULSION SYSTEM										
PROPELLANT	P&RC	PROP	N_2O_4/MMH	$>10^{13}$(D)	B	B	B	B	10^{6}(17)	
O RINGS ETC	P&RC	PROP	NYLON & CHLOROPRENE	$\sim x10^{14}$(57)	B	B	B	B	10^{7}(5)	
VALVES REGULATORS ETC	P&RC	PROP	ORGANIC SEALS ETC	10^{13}-10^{16}(D)	B	B	B	B	10^{4}-10^{6}(19)	
PYROTECHNIC ISOLATION VALVES	P&RC	PROP	EXPLOSIVES	$>10^{15}$(55)	B	B	B	B	10^{6} 10^{8}(55 56)	
DOCKING SHOCK ABSORBERS										
HYDRAULIC FLUID	DOCK	MECH	ORGANIC FLUID	$>10^{13}$(D)	B	B	B	B	10^{6} 10^{7}(57)	
SEALS ETC	DOCK	MECH	ORGANIC MATERIALS	10^{13}-10^{16}(D)	B	B	B	B	10^{4}-10^{6}(19)	
DOCKING TV MONITOR										
OPTICS	INF	MECH	TV TUBE	10^{13}(15 36)	B	B	B	B	10^{5}(15 36)	
ELECTRONICS	INF	MECH	MEDIUM FREQUENCY TRANSISTORS	10^{11}-10^{12}(7 10)	$2x10^{5}$-$2x10^{6}$(C)	$6x10^{12}$-$6x10^{13}$(C)	10^{10} 10^{11}(C)	$7x10^{6}$-$7x10^{9}$(C)	10^{3}-10^{4}(7 10)	
INFLATABLE DOCKING SEALS	DOCK	MECH	ORGANIC MATERIALS	10^{13} 10^{16}(D)	B	B	B	B	10^{4}-10^{6}(19)	
CARGO DRIVE MOTORS	C&H	MECH	LUBRICANTS	10^{16}(3, 4)	B	B	B	B	10^{9}(3 4)	
			MOTOR INSULATION	10^{14} (6)	B	B	B	B	10^{7} (6)	
CARGO CONVEYOR BELT	C&H	MECH	LUBRICANTS	10^{16}(3 4)	B	B	B	B	10^{9}(3 4)	
DOCKING STRUCTURE MATERIALS										
O RINGS & SEALS	DOCK/ ENV P	MECH	ORGANIC MATERIALS	10^{13}-10^{16}(D)	B	B	B	B	10^{4}-10^{6}(19)	
BEARING SURFACES	DOCK/ ENV P	MECH	LUBRICANTS	10^{16}(3 4)	B	B	B	B	10^{9}(3 4)	
GUIDE ARM & LATCHING LINK IMPACT SURFACES		MECH	TEFLON IMPREGNATED FIBERGLASS	10^{13}(D)	B	B	B	B	10^{4}-10^{6}(5)	
TELESCOPING SPOKE O RING		MECH	SILICON RUBBER/ TEFLON FACE	10^{13} $3x10^{14}$(D)	B	B	B	B	10^{4}-10^{6}(D)	
GASKET	DOCK		SILICONE RUBBER GASKET	$3x10^{14}$(57)	B	B	B	B	10^{6}(8)	
HUB SEALS	ENV P	MECH	ELASTOMERIC SEALS	$3x10^{14}$ $5x10^{15}$(57)	B	B	B	B	$3x10^{5}$-10^{7}(6)	
LIGHTING EQUIPMENT	C&H	CH&P	FLUORESCENT LIGHTS	10^{13}(D)	B	B	B	B	10^{5}(D)	
RADIATION MONITORING EQUIPMENT										
ACTIVE DOSIMETERS	ENV P	CH&P	SILICON SURFACE BARRIER & DIFFUSED DETECTORS	10^{12}-10^{13}(58)	$>10^{8}$(58)	10^{13}-10^{14}(58)	$\approx 10^{11}$(58)	10^{10}(58)	F	
			LITHIUM DRIFTED DETECTORS	10^{11}(58)	10^{5}(58)	$3x10^{11}$-$7x10^{11}$(59)	$\approx 10^{8}$-10^{9}(58)	10^{8}(58)	F	
PASSIVE DOSIMETERS	ENV P	CH&P	PHOTOGRAPHIC EMULSIONS	$6x10^{8}$-$4x10^{12}$(H)	B	B	B	B	$\approx 10^{2}$-10^{5}(60)	DOSES INDICATE LIMIT OF USEFULLNESS

* NEUTRON DAMAGE LEVELS FOR MATERIALS INDICATIVE OF NEUTRON INDUCED IONIZATION
A CONSIDERED TO BE DESIGNED TO WITHSTAND MISSION ENVIRONMENT OVER DURATION OF MISSION LIFE
B PRIMARY DAMAGE MECHANISM FOR THIS RADIATION ENVIRONMENT IS IONIZATION EFFECTS
C SPECIFIC DATA NOT AVAILABLE DAMAGE THRESHOLD VALUES BASED ON SILICON TRANSISTOR RADIATION EQUIVALENCIES GIVEN IN REFERENCE 64
D SPECIFIC DATA NOT AVAILABLE DAMAGE THRESHOLD CONSIDERED TO BE AT LEAST COMPARABLE TO SIMILAR MATERIALS
E SPECIFIC DATA NOT AVAILABLE DAMAGE THRESHOLD VALUES BASED ON 16 18 MEV α PARTICLE DATA GIVEN IN REFERENCE [illegible]
F PRIMARY DAMAGE MECHANISM IS BULK EFFECTS
G SPECIFIC DATA NOT AVAILABLE DAMAGE THRESHOLD ASSUMED TO BE COMPARABLE TO SILICON DEVICES
H DATA BASED ON NEUTRON EQUIVALENCIES GIVEN IN REFERENCE 29
I SPECIFIC DATA NOT AVAILABLE DAMAGE THRESHOLD VALUE BASED ON [illegible] THRESHOLD AND IONIZATION CHARACTERISTICS IN SILICON

once the damage threshold levels are identified through a combination of radiation effects data, a knowledge of the basic radiation induced phenomena underlying the damage response, and component design practice considerations.

Using the above techniques, component "degree of damage" characteristics were developed for the Space Base support subsystems. The essential results of this analysis are shown in Figure A-3 for a 1 Mev neutron environment and in Figure A-4 for ionization dose effects. The components shown are those contained in the MDAC and NAR support subsystems and are listed by generic subsystem terminology. The actual NAR and MDAC subsystems corresponding to the generic subsystems are shown in Table A-3. Three levels of damage effects are shown in Figures A-3 and A-4: threshold, moderate, and severe effects. In general, a threshold level denotes that range of accumulated radiation dose where specific effects begin to occur in the piece parts and/or materials and which would likely require some consideration in component design to insure proper subsystem operation. Moderate effects, on the other hand, generally denotes that range of radiation dose which would result in significant degradation of component performance and would require special design considerations for components to operate at this level. State-of-the-art radiation hardening design practices would be adequate to design for this radiation dose, however. The severe effects levels would seriously impair component operation, and, in many cases, new design approaches would be required. Considerable efforts would be required in order to design components to operate in this region.

Table A-3. Subsystem Correlation

NAR	MDAC	SUBSYSTEM DATA SUMMARY
EP	EP	ELECTRICAL POWER
ECLS	ECLS	ENVIRONMENTAL CONTROL AND LIFE SUPPORT
INF	DM COM OBC	COMMUNICATION AND DATA MANAGEMENT
G&C P&RC	S&AC G&N PROP	NAVIGATION AND CONTROL
C&H ENV P	CH&P	PROTECTION
DOCK	MECH	DOCKING

Radiation dose rate effects are not considered to be of any significance for the anticipated radiation environments in most of the components in the support subsystems. An exception

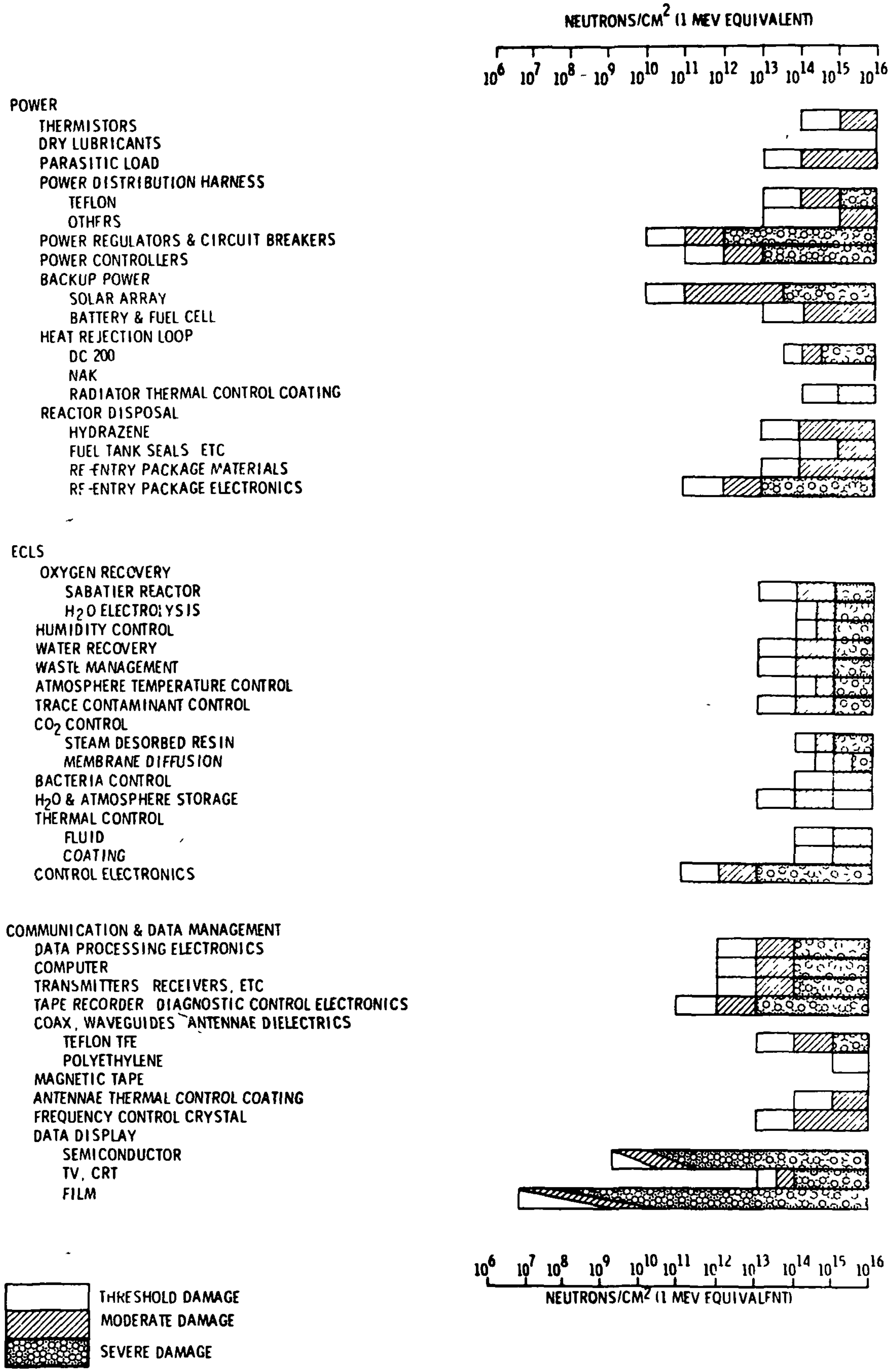

Figure A-3. 1 Mev Neutron Effects, Space Base Support Subsystem Components

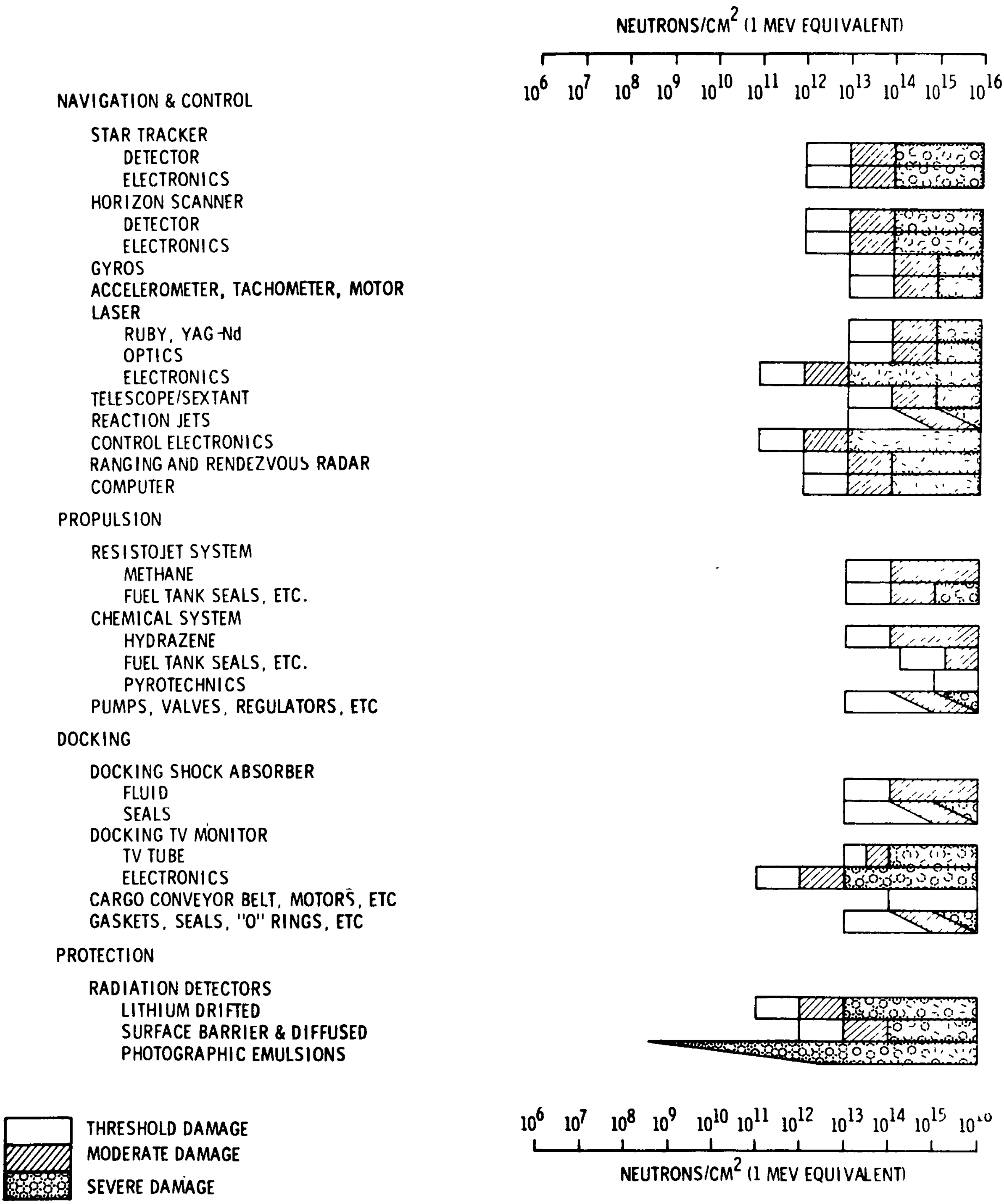

Figure A-3. 1 Mev Neutron Effects, Space Base Support Subsystem Components (Cont'd)

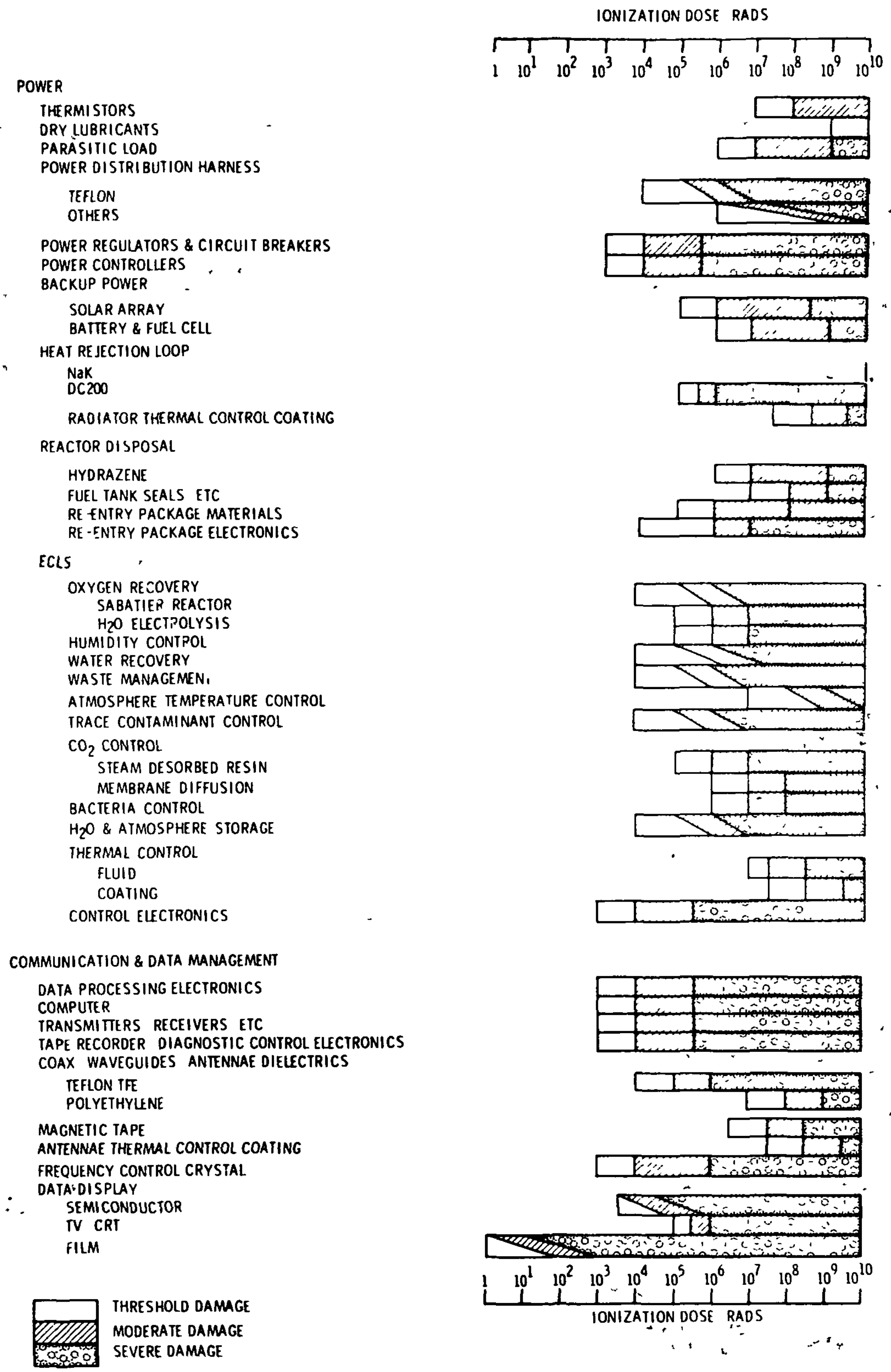

Figure A-4. Ionization Effects, Space Base Support Subsystem Components

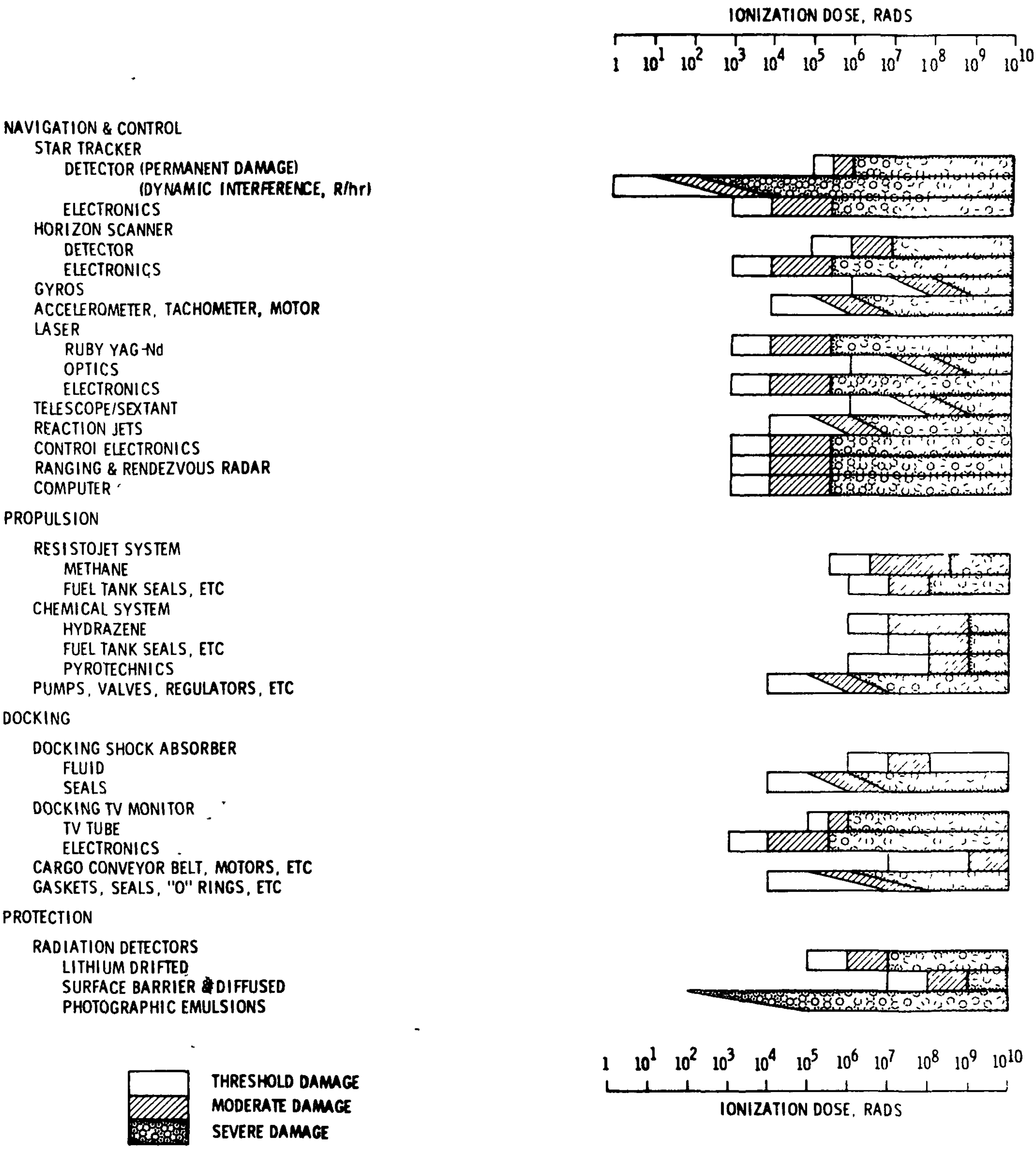

Figure A-4. Ionization Effects, Space Base Support Subsystem Components (Cont'd)

to this would be the star trackers used for navigation and control. The threshold dose rate for this unit could be approximately one to a thousand rad/hr (depending on the particular detectors used) compared to greater than a megarad/hr for other components.

An overall summary of the effects of 1 Mev neutron radiation in each of the Space Base support subsystems is shown in Figure A-5. A similar subsystem summary for the ionizing radiation environments is shown in Figure A-6. Preliminary estimates of the total radiation dose received over a 10-year mission life from both the nuclear power sources and the natural radiation environment at a 55^{o} inclination, 500 Km (270 nm) circular orbit are also given. These doses, of course, cannot be taken as accurate indications of the dose a particular subsystem will recieve, since there are obvious shielding as well as physical location configurations which must be considered in detail. However, the estimated doses will be useful in identifying those areas in which the radiation environment could impact the subsystem design cycle. The radiation doses for the natural environment were obtained from the NASA Technical Memorandum #NASA TM X-53865 entitled, "Natural Environment Criteria for the NASA Space Station Program".

The range of shielding shown for the natural environment dose corresponds to the range that the components within the support subsystems would typically be afforded. The neturon dose level given for the natural radiation environment is actually the "equivalent 1 Mev neutron dose" which would cause the same damage as the actual electron, proton, and alpha particle environments encountered. These equivalent doses were developed using the relative damage effects characteristics previously shown in Figure A-2 for these environments.

As can be seen from the subsystem summaries, the electronics as a class generally represent the more radiation-sensitive equipment as compared to the materials. However, in typical spacecraft configurations, the electronics are usually afforded more inherent shielding than that for many of the materials. Furthermore, in the case of on-board nuclear sources, the separation distance between source and component greatly determines component radiation dose. As such, the limiting item within a particular subsystem or system cannot readily be identified without an intimate knowledge of component shielding and physical location conditions.

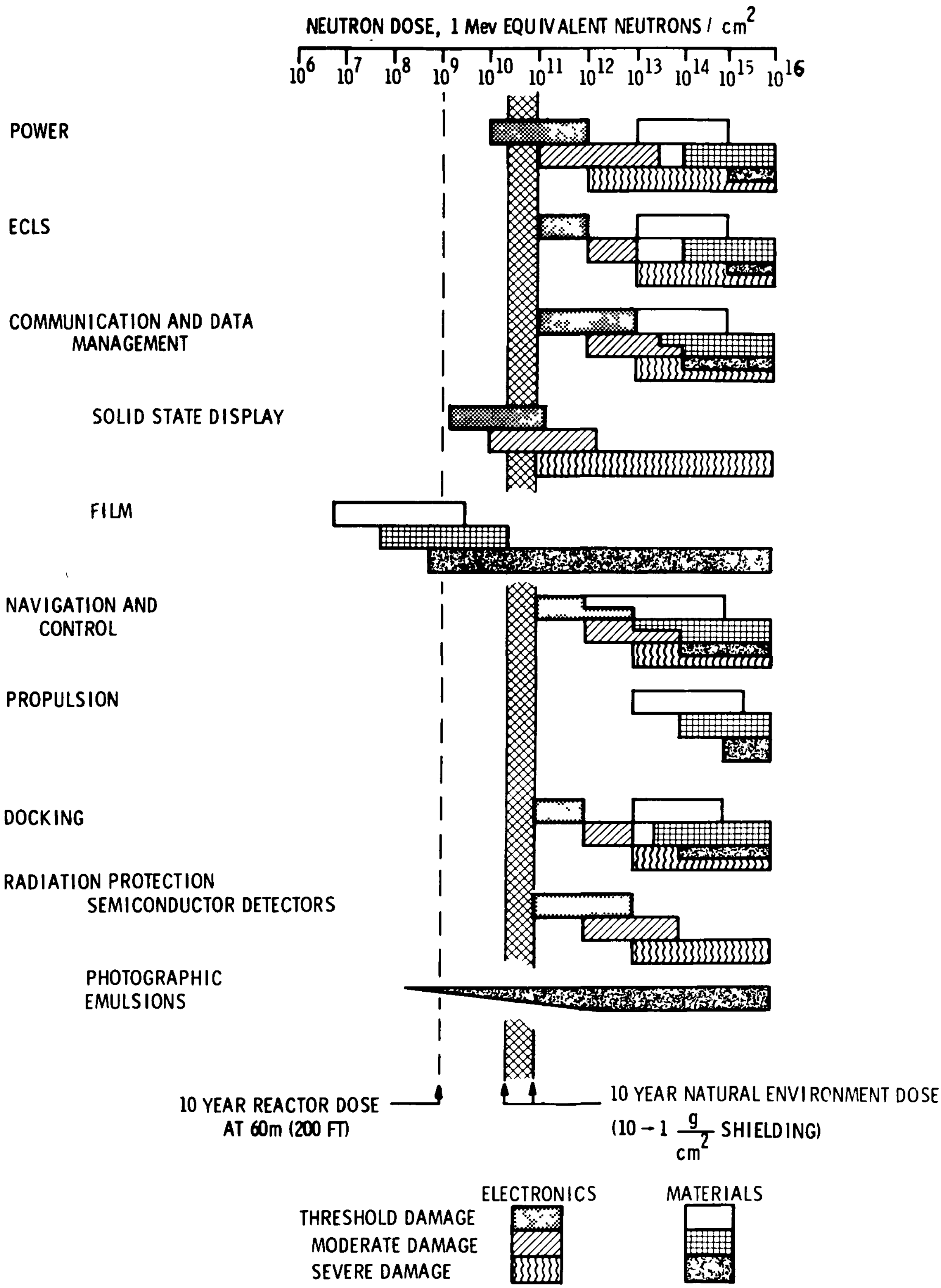

Figure A-5. Summary of 1 Mev Neutron Effects in the Space Base Support Subsystems

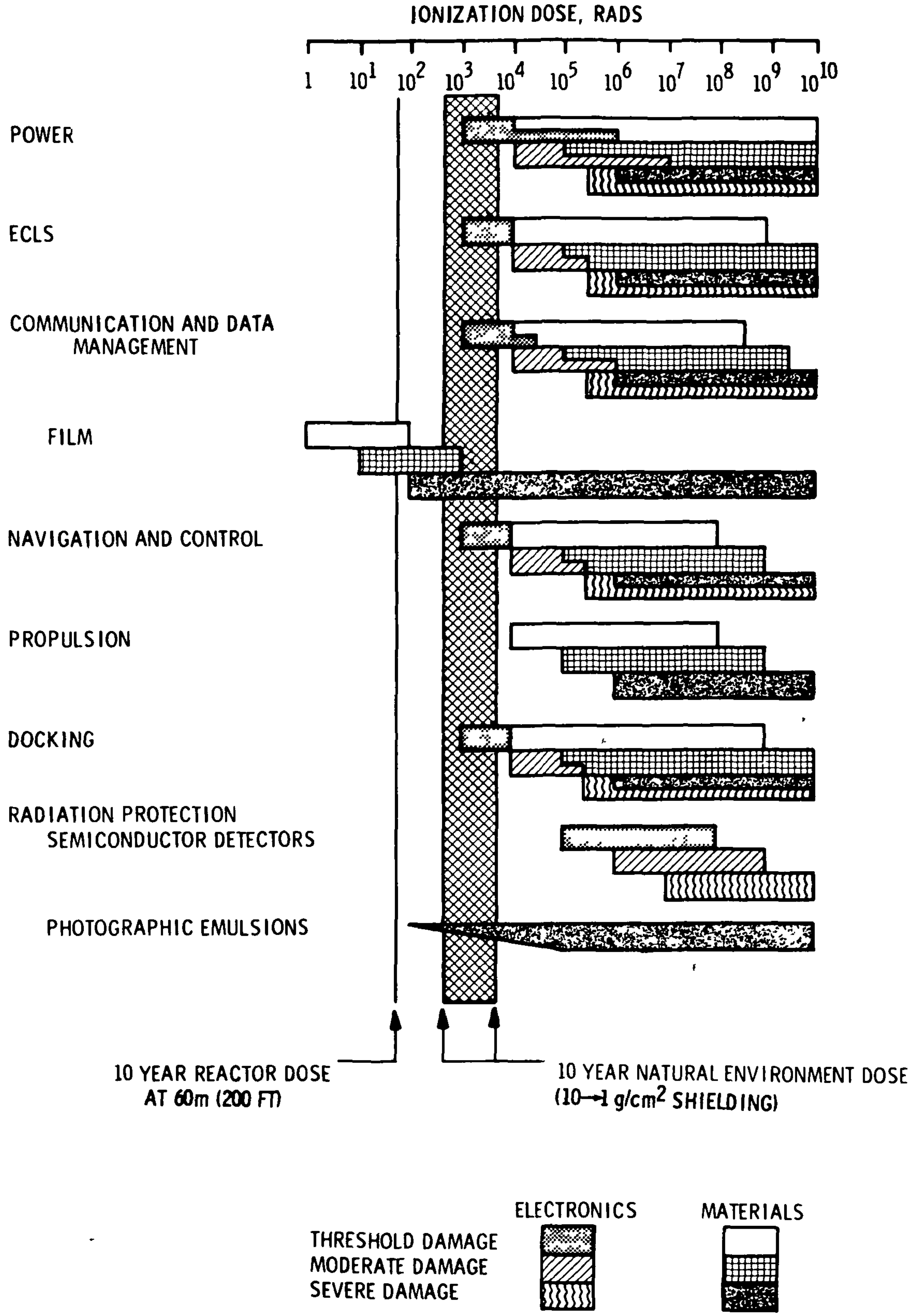

Figure A-6. Summary of Ionization Effects in the Space Base Support Subsystems

Due to the commonality of piece part and material usage, the damage thresholds for each of the subsystems are generally comparable to one another, differing by about one order of magnitude or so. An exception to this would be the film used in both the data display and radiation detection applications as well as current state-of-the-art light emitting diodes used also for data display. The wide range of component damage thresholds shown are indicative of the various parts and materials presently available which could be used in each application, some of which being much more radiation resistant than others. In view of this, an attempt was made to estimate the increase in damage threshold which could be attained considering future advances in the state-of-the-art over the next five to ten years for radiation resistant equipment together with employing judicious piece part and material selection procedures which can readily be implemented during the design process. The essential results of this analysis on a subsystem level are shown in Figures A-7 and A-8 for the neutron and ionization dose sensitivities respectively. Also shown are the estimates of the 10-year mission dose that these subsystems would receive from both the natural and nuclear radiation environments. For the system configuration assumed, the electronics would still generally represent the more sensitive equipments although over an order of magnitude increase in neutron damage threshold for the more sensitive equipments is anticipated. Ionization damage thresholds for the electronics, in particular, metal-oxide-semiconductor (MOS) and low power bipolar structures are anticipated to increase by over two orders of magnitude. Similarly, the corresponding decrease in materials sensitivity is anticipated to be about three to four orders of magnitude primarily as a result of using radiation resistant materials selection procedures.

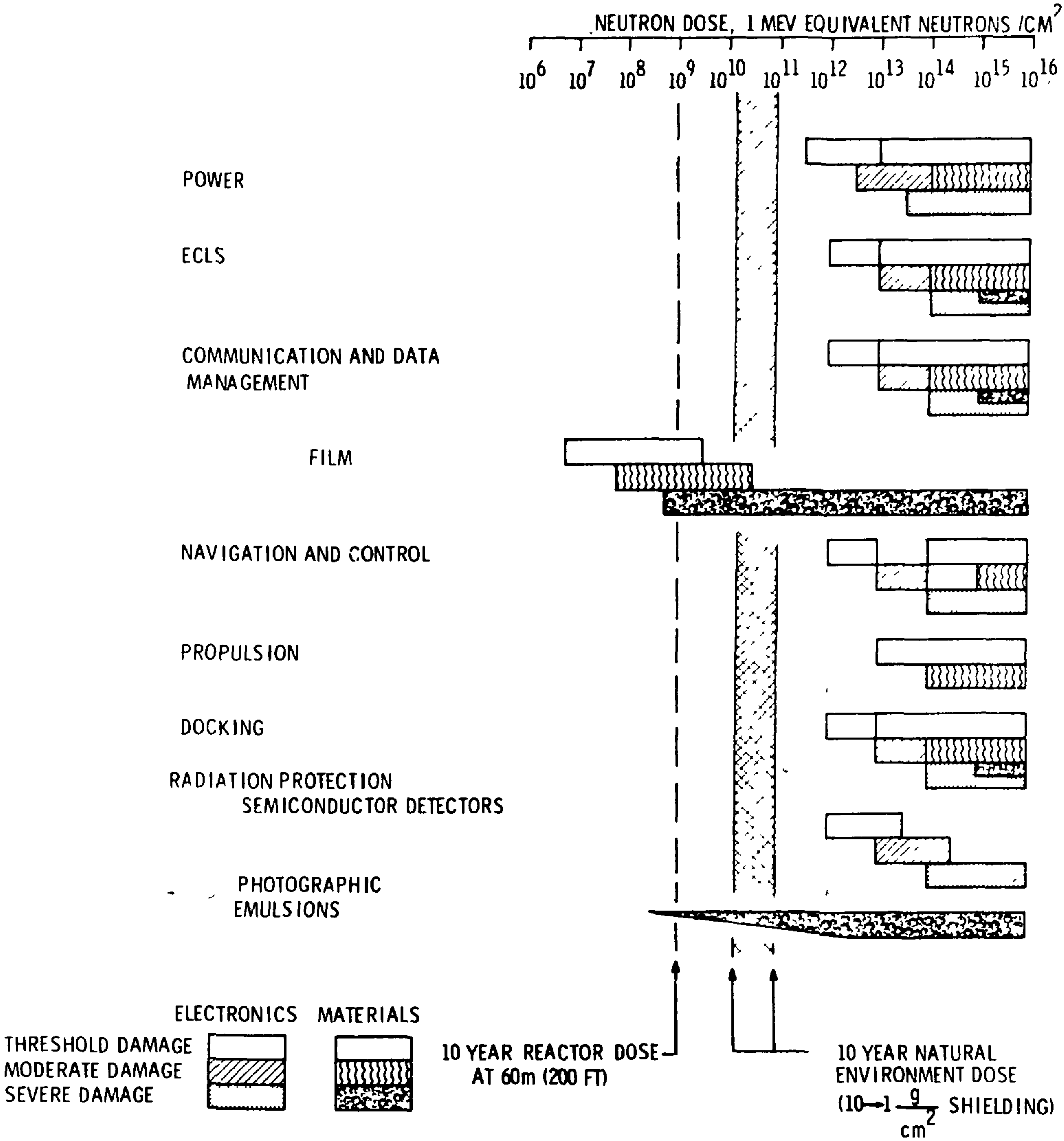

Figure A-7. Summary of 1 Mev Neutron Effects in the Space Base Support Subsystem - Future Hardening Considerations

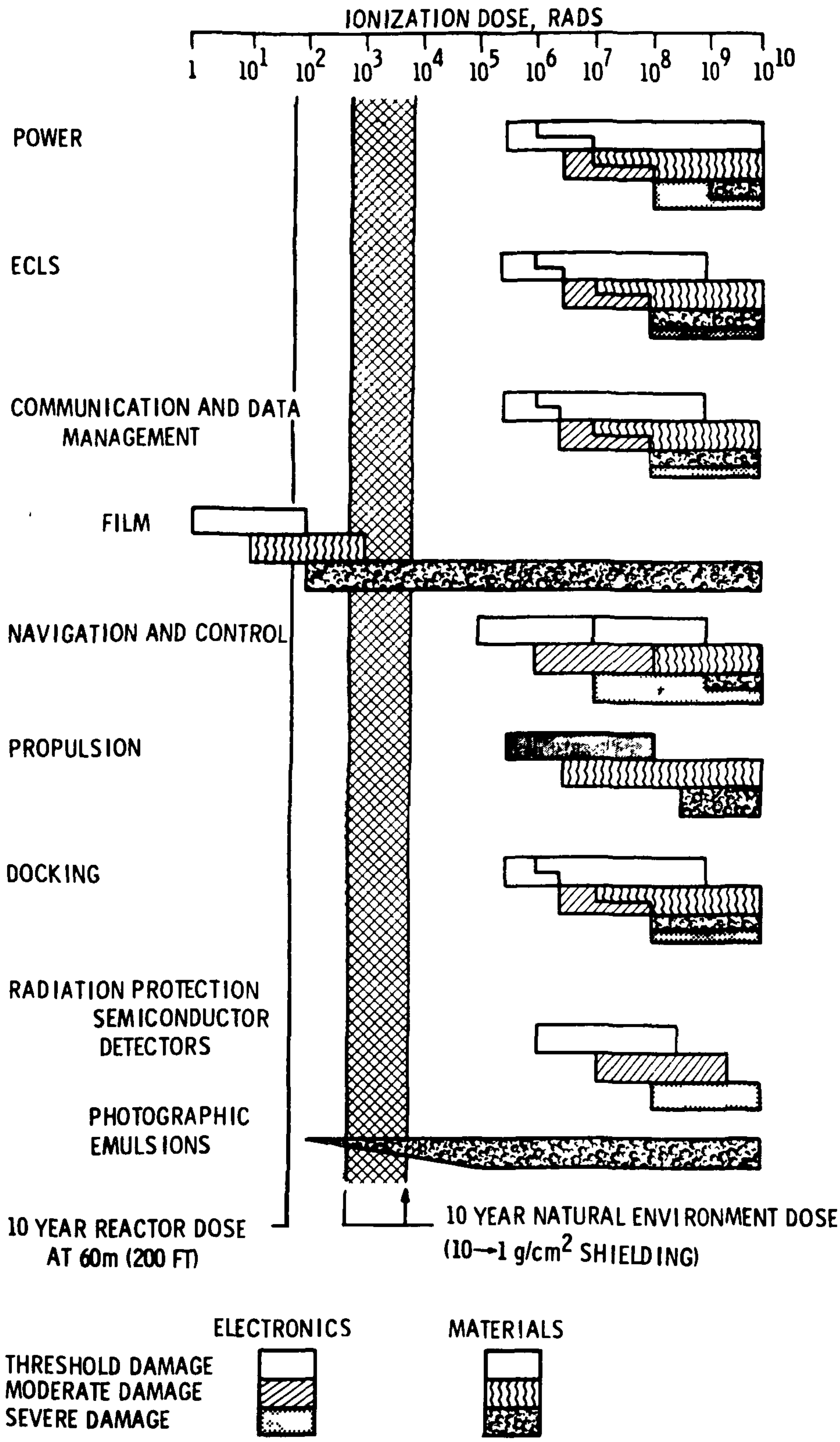

Figure A-8. Summary of Ionization Effects in the Space Base Support Subsystems - Future Hardening Considerations

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A. 3 RADIATION EFFECTS ON SPACE BASE EXPERIMENTS (NON-BIOLOGICAL)

This section contains an assessment of nuclear radiation threshold levels for "dynamic interference" and permanent damage in Space Base non-biological experiments based upon 1970 state-of-the-art. Radiosensitivity of the biological experiments is discussed in Section A. 4.

The major part of this section is concerned with dynamic interference effects; the term "dynamic interference" is explicitly meant to describe a rate-sensitive noise component which degrades the results (data) of experiments. Examples are airglow photometer saturation (Ref. A. 3-1) in the Van Allen belts and dynamic interference in sensitive gamma ray spectrometers associated with the use of on-board nuclear sources. Experiments may be separated into two interference classes: sensitive and insensitive. Here the latter term is arbitrarily applied to those experiments with interference thresholds above 10^8 particles - cm^{-2} - sec^{-1}. The dynamic interference threshold will usually mean the radiation flux causing a noise level of 1/10th of the maximum signal sensitivity for an experiment.

Permanent damage thresholds occur where minor equipment changes (such as reduced energy resolution in semiconductor radiation detectors) degrade signal quality. Only the thresholds for the most critical permanent damage are described here except in several isolated areas such as optics employing various types of glass.

The Space Base Program experiment definitions (Ref. A. 3. 2 and A. 3. 3) qualitatively describe various experiment disciplines, but are inadequate as to the type of data needed to generate threshold levels for interference. In order to obtain the experiment detail required to develop meaningful sensitivity threshold estimates, the approach used here was to consider the Space Station experiments as defined in Ref. A. 3. 4 (Experiments "Blue Book") as representative of the type of experiment complement that would be utilized on a Space Base. This approach was further justified by correlating each Space Base Experiment Discipline and its corresponding laboratories and experimental objectives with each Space Station Functional Program Element (FPE). Table A-4 shows the results of this correlation. Thus, for each Space Base Discipline, the Space Station FPE's, as grouped in Table A-4, are assumed to be typical of the experiments that would eventually make up that Discipline. The radiation sensitivity thresholds were then developed for each Discipline according to the sensitivity of each experiment within its FPE's.

Table A-4. Experiment Correlation

SPACE BASE	SPACE STATION FPE
DISCIPLINE ASTRONOMY	
ASTRONOMY EXPERIMENTS LAB	5 1 GRAZING INCIDENCE X-RAY TELESCOPE
X-RAY SURVEY TELESCOPE	5.2 STELLAR ASTRONOMY MODULE
HIGH RESOLUTION OBJECT TELESCOPE	5.3 SOLAR ASTRONOMY MODULE
ASTRONOMY SENSOR TEST PLATFORM	5 4 U.V. STELLAR ASTRONOMY SURVEY
MODULE ACCESS FACILITY - ASTRONOMY	5.5 HIGH ENERGY STELLAR SURVEY
FAINT OBJECT SURVEY TELESCOPE	5.21 IR STELLAR SURVEY
DISCIPLINE· PHYSICS	
PHYSICS MODULE LAB	5 6 SPACE PHYSIC AIRLOCK EXPERIMENTS
PHYSICS MODULE LAB	5.7 PLASMA PHYSICS & PERTURBATIONS
COSMIC RAY/HIGH ENERGY PHYSICS	5 8 COSMIC RAY PHYSICS LAB
DISCIPLINE - ADVANCED TECHNOLOGY	
	5 17 CONTAMINATION MEASUREMENTS
DATA ANALYSIS LAB	5.18 EXPOSURE EXPERIMENTS
SENSOR CONTROL LAB	5 19 EXTENDED SPACE STRUCTURE DEVELOPMENT
SENSOR PLATFORMS	5.20 FLUID PHYSICS IN MICROGRAVITY
FLUID PHYSICS LAB	5 22 COMPONENT TEST AND SENSOR CALIBRATION
	5 24 MSF ENGINEERING & OPERATIONS
DISCIPLINE· EARTH SURVEYS	
DATA ANALYSIS LAB SENSOR CONTROL LAB SENSOR PLATFORMS	FPE 5.11 EARTH SURVEYS
MANEUVERABLE SUBSATELLITE	5 12 REMOTE MANEUVERING SUBSATELLITE
DISCIPLINE BIOMEDICAL	
BIOMEDICAL AND BEHAVIORAL LAB	5.13 BIOMEDICAL AND BEHAVIORAL RESEARCH
BIOSCIENCE CENTRIFUGE	5.13C CENTRIFUGE
CONTROLLED BIOMEDICINE ENVIRONMENT LAB	5.14 MAN-SYSTEM INTEGRATION
	5 15 LIFE SUPPORT AND PROTECTION SYSTEM
DISCIPLINE· BIOSCIENCES	
BIOSCIENCE LAB	5.9 SMALL VERTEBRATES
	5.10 PLANT SPECIMENS
AGRONOMY AND FOOD SCIENCES LAB	5.25 MICROBIOLOGY
	5.26 INVERTEBRATES
DISCIPLINE· CHEMISTRY	
CHEMICAL KINETICS CHEMICAL ANALYSIS LAB ADVANCED TECHNOLOGY LABS GENERAL SUPPORT FACILITIES	5 27 PHYSICS AND CHEMISTRY LAB
DISCIPLINE· SPACE MANUFACTURING	
MATERIALS PROCESSING LAB MATERIALS ANALYSIS LAB	5.16 MATERIALS SCIENCE AND PROCESSING

The following sections briefly describe the approach followed in developing the sensitivity thresholds and present detailed data tables and summary charts of the results. Supporting data particularly on radiation sensors, photo-film and optics is presented in Section A.3.4.

A.3.1 APPROACH

This section describes the methods applied to each Space Station FPE to determine the radiation thresholds, for the Space Base Disciplines. Much of the detailed data utilized here is presented in the Supporting Data.

A.3.1.1 Interference Thresholds (Flux)

Interference thresholds were determined for separate particle environments so that with appropriate weighing factors, they can be used in later study tasks for various baseline environments. The separate monoenergetic particle fields for which interference threshold were developed are as follows:

Neutrons (1 Mev),

Electrons (1 Mev),

Protons (30 Mev),

Gamma Rays (1 Mev).

These particle fields are representative of the more penetrating components of reactors and natural radiation environments although they are vastly simplified.

Unfortunately interference data in the literature directly usable for Space Base experiments is limited. A compensation is that many experiments will not suffer a loss in data quality due to interference if properly designed.

The method employed to develop the interference thresholds is as follows:

1. First, perform a cursory analysis of the experiments, employing the guidelines as described in Section A.3.4 to select those which may be radiation sensitive.

Experiments judged sensitive typically are concerned with measurement of electromagnetic radiation (excluding RF or MW antennas) or with measurement of energetic neutral or charged particles. Thus radiation and optical sensors are included. Experiments which are sensitive to interference at 10^8 particles - cm^{-2}-sec fall into the insensitive category.

2. Investigate experiment parameters, in detail, as readily available via the Blue Book, generic data, etc.

   These parameters include maximum sensitivity, dynamic range, signal to noise ratio and probable environment to be sensed. Also required is detail regarding "optics" and sensors, such as counter efficiency, collection areas, types of discrimination, materials used, and other relevant factors.

3. Using data, analyses, and simplified methods, estimate the response of sensors to each of the four particle environments and set the threshold for interference at those flux values for which the true signal/interference noise ratio is one-tenth of the maximum sensitivity. In cases where the probable Space Base environment includes background nuclear radiation species identical to those in experiments, an additional specification of interference is noted in the estimates. Generally, no experiment shielding is assumed at this level of response estimation.

4. Experiments utilizing film, as mentioned in Ref. A.3.4, have a data quality problem which is listed as an interference threshold.

A.3.1.2 Permanent Damage Threshold (Cumulative Exposure)

Permanent damage thresholds were estimated on the basis of cumulative ionizing radiation dose (in units of rads) and equivalent 1 Mev neutron fluence (n/cm^2). The method for reducing any environment to an equivalent 1 Mev neutron environment has been previously covered in Section A.2. Several assumptions are made here:

1. Generally only the most limiting thresholds were established,

2. No allowance was made for long term annealing, and in particular, for some cooled semiconductor devices this implies more damage than for room temperature devices and,

3. Each experiment was assumed to have integral electronics systems.

Photo film damage thresholds were estimated on the basis of the probable generic types of film used in experiments.

A.3.2 RADIATION EFFECTS THRESHOLDS - DETAILED DATA TABLES

This section is comprised of the detailed results of flux and dose thresholds for experiments (non-biological) typical of a Space Base Program.

Detailed radiation thresholds for experiments are presented in Table A-5 for each Space Base discipline. Brief discussions are given below generally describing the basis of the threshold estimates for each experiment discipline. The Astronomy Discipline is discussed in more detail than the others since its sensors are typical of those used in other disciplines. More detailed discussions of each experiment may be found in (Ref. A.3.4).

DISCIPLINE: ASTRONOMY

FPE 5.1 GRAZING INCIDENCE TELESCOPE

This X-ray telescope FPE is designed to allow interchange of 4 different experiment packages at its focus. There interference thresholds are discussed separately below:

Polarimeter - The 8 G-M tubes have a total collection area of 500 cm^2; hence with a GM tube sensitivity of 2 x 10^{-3} counts/photon -cm^{-2} the interference is 1 count per photon (1 Mev)-cm^{-2} -sec^{-1}. Now the system sensitivity to the sensed radiation, low kev X-rays, is 10^3 cm^2 (collection area) x (1 X-ray -cm^{-2}-sec^{-1}) = 10^3 X-rays-sec^{-1}. Thus for a signal-to-nose ratio of 10, the interference threshold for 1 Mev gamma-rays=10^2 photons-cm^{-2}-sec^{-1}. The experiment uses a large mass of hydrogen to scatter X-rays into the G-M tubes; neutron interactions in this hydrogen are relatively efficient and hence the neutron interference threshold is set at 10 times that for gammas. Anticoincidence shielding will be effective in eliminating interference by protons and electrons; however, a few hundred microseconds (resolving) time is lost per successful discrimination. In addition, some protons and electrons will enter the G-M tubes directly through the open solid angle of the telescope. The interference threshold for protons and electrons is 10 particles-cm^{-2}-sec.

Table A-5. Radiation Effects

ASTRONOMY

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE: Sensed Radiation	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5.1 GRAZING INCIDENCE X-RAY TELESCOPE											
Polarimeter Ref 9, 15 16	Sensitivity Energy - 1-4 kev Flux - 1 photon - cm^{-2}-sec^{-1} Collection area - 1000 cm^2	8 G-M tubes Net area = 500 cm^2 Hydrogen Scatterer	10	0.1 photon (1-4 kev)	10^1	10^1	10^2	10^3	Electronics	10^4	10^{12}
Curved Crystal Spectrometer Ref 9, 17	Sensitivity Energy - 0.5-8.27 kev Flux - 1 photon-cm^{-2}-sec^{-1} Collection area - 1000 cm^2	G-M tubes plus CsI anti-coincidence shield	10	0.1 photon (0.5-8.27 kev)	10^4	10^4	10^3	10^4			
High Resolution Source Studies Ref 13, 17	X-ray Sensitivity Energy - 0.2-4 kev Sensitivity - 10^{-12} ergs - cm^{-2}-sec Collection area - 1000 cm^2	Photo film Channel electron Imager	10	0.1-X-ray (0.2-4 kev)	10^2	10^2	10^3	10^4		0.1-1.0	
Maximum Sensitivity X-Ray Detector Ref 21f	X-ray Sensitivity Energy - 0.5-4 kev Sensitivity - 1 photon - cm^2 - sec Collection area - 1000 cm^2	Si(Li) Detectors, actively shielded	10	0.1 X-ray (0.5-4 kev)	10^2	10^2	10^2	10^3	Si(Li) Detectors		10^{11}

Table A-5. Radiation Effects (Cont'd)

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	INTERFERENCE: S/N Goal	INTERFERENCE: Sensed Radiation	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Protons (30 Mev)	Flux Thresholds: Electrons (1 Mev)	Flux Thresholds: Photons (1 Mev)	Flux Thresholds: Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Fluence Thresholds: Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 2 ADVANCED STELLAR ASTRONOMY									Electronics	10^4	10^{12}
Field Image TV **Ref 13**	**Wavelength Sensitivity-** **0 09-10 microns** **Telescope** **3M Apertures** **12M Focal length**	**TV Camera** **(10^{-5} ft-candles)**	10	N/A	10^5	10^6	10^7	10^7			
Plate Cameras	**70, 225mm**	**Photo Film**								1-10	
Concave Grating Spectrograph **Ref 13**	**Spectral Sensitivity-** **0 08-0 3 microns** **Resolution -** **1 angstrom** **Resolution -** **110 lines/mm** **10^{-5} ft-candles**	**Photo Film**								1-10	
		Videographic	10	N/A	10^6	10^7	10^8	10^8			

Table A-5. Radiation Effects (Cont'd)

ASTRONOMY

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE: Sensed Radiation	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 3 ADVANCED SOLAR ASTRONOMY									Electronics	10^4	10^{12}
1 5 M U V - Vis Telescope	Wavelength Sensitivity- 0 0-1 0 micron	Photo Film								0 1-10	
		Photomultiplier Tubes	10	N/A	10^3	10^3	10^4	10^5			
		TV Vidicons	10	N/A	10^6	10^7	10^8	10^8			
1/4 M XUV Spectro-heliograph	N/A	Photo Film Image Vidicon	10	N/A	10^5	10^6	10^7	10^8		0 1-10	
X-Ray Telescope Ref 9, 25	0 5 Meter Aperture Wavelengths - 1-24 angstroms Resolution Spatial - 2 arc-sec Sensitivity - 0 1 photon - cm^{-2}-sec^{-1}	Proportional Counter ($10\ cm^2$ area)	10	0 1 X-rays	10^1	10^1	10^2	10^3			
		Channel Multiplier Detectors	10	0 1 X-rays	10^2	10^2	10^3	10^5			
5 4 ULTRAVIOLET STELLAR SURVEY									Electronics Optics	10^4 10^5 0 1-50	10^{12}
U V Spatial Survey Ref. 9, 21b	Wavelengths - 0.18-0.3 microns Sensitivity - ≤ 6th magnitude stars	Photo Film									
		TV Camera	10	N/A	10^6	10^6	10^7	10^7			
Schmidt Spectrograph	Wavelengths - 0 1-0 2 microns	Image Converter Ahead of Photo Film	10							0 1-10	

Table A-5. Radiation Effects (Cont'd)

ASTRONOMY

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	S/N Goal	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (10 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5.5 HIGH ENERGY STELLAR SURVEY									Electronics	10^4 0.1-10	10^{12}
X-Ray Telescope Ref 9, 25	Collection area - 100 cm^2 Energy Range - 0.1-4 kev, x-rays	Photo Film Thin Window Proportional counter with CsI anti-coincidence shield	10	0.5 x-rays	10^3	10^3	10^2	10^5			
X-Ray Spectroscopy Ref 9	X-Ray Energy Range - 0.1-8 kev	Proportional Counter	10	5 x-rays	10^4	10^4	10^4	10^5			
		Image Amplifier/Vidicon	10	5 x-rays	10^4	10^5	10^6	10^7			
Nuclear Gamma Ray Spectrometer	Detector - 1x1x3 in	Ge(Li) Detectors cooled	1	10^{-5} photons (discrete energies in range 0.5-3 Mev)	10^3	10^3	1	10^1	Ge(Li) Detector		10^{11}
Nuclear Emulsion/Spark Chamber Gamma Ray Spectrometer Ref. 26, 9	Photon Energy - $>10^2$ Mev Photon Flux $>10^{-7}$ γ-cm^{-2}-sec^{-1}	Cerenkov Counters	10	0	$>10^8$	10^2	10^4	10^4		0.01-0.1	
		Nuclear Emulsion	1	0	10^2	10^2	10^1	10^2			
		Spark Chamber Scintillator/PMT	1	0	10^2	10^2	10^2	10^3			

Table A-5. Radiation Effects (Cont'd)

ASTRONOMY

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE: Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 21 INFRARED STELLAR SURVEY									Electronics	10^4	10^{12}
Interferometer Ref 27	Wavelengths 0 7-1000 microns Aperture - 1M Dia Focal Length - 10M	Cooled Thermister Bolometer (T=1 5°K)	5	N/A	10^4	10^5	$2x10^5$	$3x10^5$			
D C Radiometer Ref 27		Ge Hg Detector (T=35°K)	5	N/A	10^2	10^2	$2x10^3$	$2x10^4$	Ge Hg Detector		10^{11}
IR Detector Array Ref 27		Ge Hg Detectors	5	N/A	10^2	10^2	$2x10^3$	$2x10^4$	Ge Hg Detector		10^{11}

Table A-5. Radiation Effects (Cont'd)

PHYSICS

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE: Flux Thresholds-Particles-cm^{-2}-sec^{-1} — Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds — Ionization Rad	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 6 SPACE PHYSICS AIRLOCK EXPERIMENTS									Glass Electronics	10^4	10^{12}
Ultraviolet Light Airglow	N/A	Photo Film								0 1-10	
Gegenschein, Zodiacal Light	10-10^4 Stars (M-10) per square degree of sky 30 sec exposure **Wavelengths Bands at 0 43 and 0 55 microns**	Photomultiplier Photo Film	10	N/A	10^2	10^2	10^4	10^5		0 1-1	
Coronagraph Contamination Measurement	**N/A**	**Photo Film**								0 1-10	
Contamination Measurement Experiment	**N/A**	**Photomultiplier** **Photo Film**	10	N/A	10^3	10^3	10^4	10^5		0 1-10	
Environmental Composition	**Ions Neutral Particles** **0-100AMU** **>100AMU**	**PMT in Mass Spectrometer**	10	N/A	10^4	10^4	10^5	10^6			

Table A-5. Radiation Effects (Cont'd)

PHYSICS

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE — Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 7 PLASMA PHYSICS AND ENVIRONMENTAL PERTURBATION										10^4	10^{12}
Plasma Wake	**Ion Energies:** ± 10ev	Faraday Cup 6 in dia, screened	10	N/A	10^5	10^5	$\sim 10^{10}$	$\sim 10^{10}$			
Cyclotron Harmonic Resonance	**Electrostatic Wave Observation**	**Photo Film (Oscilloscope)**								0 1-1	
Accelerator Experiment	**0-20 Kev electrons, protons**	Image Orthicon	10	10^5	10^6	10^7	10^8	10^8			
		Geiger Counter	10	10^5	10^2	10^2	10^3	10^5			
		Optical Spectro-graph	10	0	10^2	10^2	10^3	10^4			
Plasma jet		**Photo Film**								0.1-10	
5.8 COSMIC RAY PHYSICS LABORATORY									**Electronics**	10^4	10^{12}
Ionization Spectrograph	**Proton Energy - 10^{10}-10^{15} ev**	**Photo Film**								0.01-0.1	
	Flux - $\sim 10^{-6}$ particles-cm^{-2}-sec, with E $>10^{10}$ev	**Spark Chamber**	10	0	10^2	10^2	10^2	10^3			
		Scintillation Counter	10	0	10^2	10^2	10^2	10^3			
		Cerenkov Counters	10	0	10^6	10^3	10^6	10^4			
		Proportional Counters	10	0	10^2	10^2	10^3	10^4			

Table A-5. Radiation Effects (Cont'd)

EARTH SURVEYS

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	S/N Goal	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5.11 EARTH SURVEYS									Electronics	10^4	10^{11}
Metric Camera	High resolution	Photo Films								0.1-50	
Multispectral Camera	Medium resolution and simultaneous pictures with different filters										
Radar Imager	High resolution										
Multispectral IR Scanner Ref 27	Wavelength - 0.5-13 microns	Photomultiplier Tubes	10	N/A	10^3	10^3	10^4	10^5			
		Silicon Detector	10	N/A	10^4	10^4	10^5	10^6			
		HgCdTe Detector (cooled)	10	N/A	10^3	10^3	10^4	10^5	HgCdTe		10^{11}
Visible Wavelength Polarimeter	Narrow spectra in 0.38-0.58 micron region 2 min data collection/sample	Photomultiplier Tube	10	N/A	10^3	10^3	10^4	10^5			
Absorption Spectrometer	8 in Aperture Telescope SO_2, O_2 absorption bands	Photo Film Photomultiplier Tube	10	N/A	10^3	10^3	10^4	10^5		1-50	
UV Imager/Spectrometer	Wavelengths - 0.35-0.40 microns	Image Dissector Tube	10	N/A	10^6	10^6	10^7	10^8			
Photo-Imaging Camera	Extremely high resolution, in 4 narrow light bands 5 sec readout/TV	TV	10	N/A	10^5	10^5	10^7	10^8			

Table A-5. Radiation Effects (Cont'd)

EARTH SURVEYS

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	INTERFERENCE: S/N Goal	INTERFERENCE: Sensed Radiation	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Protons (30 Mev)	Flux Thresholds: Electrons (1 Mev)	Flux Thresholds: Photons (1 Mev)	Flux Thresholds: Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Fluence Thresholds: Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 12 REMOTE MANEUVERING SUBSATELLITE									Electronics	10^4	10^{12}
Plasma Wake Experiment	N/A	TV Vidicon	10	N/A	10^5	10^6	10^7	10^8			

Table A-5. Radiation Effects (Cont'd)

ADVANCED TECHNOLOGY

FPE Experiment References	Experiment Parameters	Sensitive Component	S N Goal	INTERFERENCE: Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 17 CONTAMINATION MEASUREMENTS									Electronics Materials	10^4	10^{12}
Sky Background Brightness — **Ref 9, 13**	**Sensitivity - 10^{-18} w-cm^2-sec (Visible Light) w/o optics magnification**	Photomultiplier I cm^2 area	1	N/A	30	30	3000	$3x10^4$			
Particle Size, Distribution — **Ref. 9, 6, 20**	**Sensitivity - $4x10^{-7}$ ft candles**	Coronagraph Image Intensifier (ahead of Vidicon)	10	N/A	$2x10^5$	$2x10^6$	10^7	10^8			
Cloud Composition — **Ref. 12**	**Mass Range - 0-100 AMV Charge/Ion - Neutral or Positive**	PMT in Mass Spectrometer	1	N/A	10^4	10^4	10^5	10^6			
Optical Surfaces Degradation — **Ref. 9**	**Measures reflectivity and transmittance in various optical bands**	Photometer	10	N/A	$2x10^4$	$2x10^5$	$2x10^6$	$2x10^7$			
Contamination Dispersal Measurements	N/A	Photo Film								1-10	

Table A-5. Radiation Effects (Cont'd)

ADVANCED TECHNOLOGY

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	INTERFERENCE: S/N Goal	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5.18 EXPOSURE EXPERIMENTS									Electronics	10^4	10^{12}
Impact Flash Spectrometer	Sensitive Wavelengths- 0 3-0.9 microns Short Time Exposure	Photo Film								1-10	
Meteor Flash Analyzer	Sensitive to 0.2-0 4μ 30° field of view (of earth), at night	Three-Channel Radiometer	10	N/A	$2x10^4$	$2x10^5$	$2x10^6$	$2x10^7$			
5.19 EXTENDED SPACE STRUCTURE DEVELOPMENT		None								N/A	N/A
5.20 FLUID PHYSICS IN MICROGRAVITY									Electronics	10^5	10^{12}
Various Experiments	1 ft-candle	Vidicon Photo Film	10	N/A	$\geq 10^8$	$\geq 10^9$	$\geq 10^{10}$	$\geq 10^{10}$		1-100	
5.22 COMPONENT TEST & SENSOR CALIBRATION									Electronics	10^4	10^{12}
Microwave Radiometer	Sensitivity - 10^{-8} watt/cm^2	Detector	10	N/A	$2x10^2$	$2x10^3$	$2x10^5$	$2x10^6$			
Long Wave Infrared Sensor (LWIR)	Sensitivity - Noise - 10^{-10} watts-cm^{-2} Range - 8-12 microns Resolution - 200 feet (on earth surface) Aperture - 25 Cm (at f/6)	Ge.Hg Detector (at 20°K)	100	N/A	20	$2x10^2$	$2x10^4$	$2x10^5$	GeHg		10^{11}
Various Experiments	Still Photography	Photo Film								1-100	

Table A-5. Radiation Effects (Cont'd)

ADVANCED TECHNOLOGY

FPE Experiment References	Experiment Parameters	INTERFERENCE: Sensitive Component	INTERFERENCE: S/N Goal	Flux Thresholds-Particles-cm^{-2}-sec^{-1}: Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds: Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 24 ENGINEERING AND OPERATIONS									Electronics	10^4	10^{12}
Star Tracker	Stability - 10^{-2} arc-sec	Photomultiplier Tube	10	N/A	10^2	10^3	10^4	10^4			
	10^{-3} ft-candles	Vidicon	10	N/A	10^7	10^8	10^9	10^9			
	10^{-5} ft-candles	Image Orthicon	10	N/A	10^5	10^6	10^7	10^7			
Optical Radar	Range - 200 nm Aperture - 3 in.	Photomultiplier Tube	10	N/A	10^3	10^4	10^5	10^5			
Laser Communication	Bandwidth - 100 MHz Wavelength - 10 6 microns	Laser Photo Diode	10	N N/A	10^3	10^3	10^4	10^5			

Table A-5. Radiation Effects (Cont'd)

VARIOUS DISCIPLINES

FPE Experiment References	Experiment Parameters	Sensitive Component	S/N Goal	INTERFERENCE: Flux Thresholds-Particles-cm^{-2}-sec^{-1} Sensed Radiation	Protons (30 Mev)	Electrons (1 Mev)	Photons (1 Mev)	Neutrons (1 Mev)	PERMANENT DAMAGE: Sensitive Components	Fluence Thresholds Ionization Rads	Bulk Damage Neutrons-cm^{-2} (1 Mev)
5 13 BIOMEDICAL AND BEHAVIORAL RESEARCH									Electronics	10^4	10^{12}
5 13C CENTRIFUGE			Videographic sensors	N/A	10^6	10^7	10^8	10^8			
5 14 MAN-SYSTEM INTEGRATION											
5 15 LIFE SUPPORT AND PROTECTION SYSTEM			Photo Film							1-100	
5 9 SMALL VERTEBRATES		Photo Film							Electronics Organics	10^4 1-100	10^{12}
5 10 PLANT SPECIMENS											
5 25 MICROBIOLOGY											
5 26 INVERTEBRATES											
Radiotracer Monitoring		Various Radiation Detectors			10^3	10^3	10^4	10^5			
		Photo Film								1-100	
5 27 PHYSICS & CHEMISTRY LAB										10^3	10^{12}
Various		Photo Film								1-100	
5 16 MATERIALS SCIENCE AND PROCESSING										10^4	10^{12}
		Photo Film								1-100	

NOTES

1 Abbreviations N.A. stands for not available, N/A stands for not applicable

2 Photofilm (including emulsions) may not be listed in more than one experiment per FPE, even if called out in the Blue Book

3 Neutrons of the thermal energy range have enhanced probability of causing activation of many atomic elements. They were not considered here as an (eventual) source of interference in part because of a lack of knowledge as to materials selection. In addition, thermal neutrons will principally originate in nuclear power sources (and their shields), shielding, of optimum weight, if required by restrictions on dose to man would be best located adjacent to these sources

4 References for data for photofilm, glass and photomultiplier tubes are in Appendix C and are not repeated in applicable areas of Table 4-1

Curved Crystal Spectrometer - This experiment uses a number of very small G-M tubes and their effective collection area is 50 cm^2. Hence, the approximate photon interference threshold is ten times higher than that above for the polarimeter. The neutron interference threshold is conservatively raised by ten, also. The use of CsI anti-coincidence shields is expected to reduce proton and electron interference by a factor of ten over that for 1 Mev photons.

High Resolution Source Studies - This experiment will amplify X-ray images with a channel electron multiplier (CEM, gain 10^5) ahead of a vidicon. Hence the CEM is the sensitive component. At 3×10^{-4} counts/1 Mev. photon-cm^{-2}, and an assumed CEM area of 20 cm^2 the interference is 6×10^{-3} counts per photon-cm^{-2}-sec^{-1}. Now, at unit efficiency to X-rays, the response of the CEM is 50 counts per X-ray-cm^{-2}-sec. Therefore the threshold 1 Mev photon flux, at an S/N of 10, is 10^3 photons-cm^{-2}-sec. The threshold for neutron interference, being sensitive to various near-by materials, is conservatively set ten times above that for gamma rays. Protons and electrons are assumed to have unit efficiency of producing interference counts, if arriving from the field of view; assuming the field of view is 1/20th of the full sphere around the CEM and the particles are arriving isotropically, then the threshold fluxes are 5 x 20, or 10^2 particles-cm^{-2}-sec^{-1}. No pulse height discrimination has been assumed here.

Maximum Sensitivity X-ray Detector - Assuming the Si(Li) detector area is 10 cm^2 and the sensitivity for 1 Mev photons is 10^{-3} counts/photon-cm^2, the interference is 10^{-2} counts per photon-cm^{-2}-sec^{-1}. Now, with a collection area of 100 cm^2, and a S/N ratio of 10, the threshold flux to produce 10 counts/sec is 10^2 gammas-cm^{-2}-sec^{-1}. Similar comments to those above apply to neutrons, protons and electrons.

FPE 5.2 ADVANCED STELLAR ASTRONOMY

This FPE is designed to record starfield optical images and optical star spectra, using either videographic or photo film data collection media.

Field Image TV - This experiment will employ an image orthicon as a light sensor behind a 3M telescope. The image orthicon is assumed to have a maximum sensitivity of 10^{-5} ft-candles, or 5×10^7 photons-cm^{-2}-sec. At a signal to noise ratio of 10, a threshold particle flux must produce interference effects comparable to 5×10^6 photons ($\sim$2 ev)-cm^{-2}-sec^{-1}. For gamma rays, using the interference data for PMT's (10^{-3} counts-$photon^{-1}$) and estimating 10^3 optical

photons (avg) per interference event, the threshold flux would be 10^7 photons-cm^{-2}-sec^{-1}. With higher interaction rates, the threshold fluxes for electrons and protons are estimated to be 10 and 10^2 times higher, respectively. The threshold for neutrons is estimated at 10^7 n-cm^{-2}-sec^{-1}.

Concave Grating Spectrograph - This experiment will employ a TV camera to record UV star spectrographs. Since most interférence events will randomly illuminate the camera photo cathode, whereas the spectra will be ordered, the interference flux levels are estimated to be an order of magnitude larger than discussed above for the Field Image TV.

FPE 5.3 ADVANCED SOLAR ASTRONOMY

1.5 Meter Telescope - Besides employing photofilm and TV vidicons, there will also be a photomultiplier tube (PMT) for optical data collection. When filtering is used to look at narrow spectra bands, the PMT may be used near its maximum sensitivity. Assuming a maximum sensitivity of 200 photons-cm^{-2}-sec, and a signal to noise ratio of 10, together with the TRW data of 2 x 10^{-3} count/photon results in a gamma threshold of 10^4 photons-cm^{-2}-sec^{-1}. For the other particle radiations the threshold fluxes are adjusted to their interaction characteristics.

X-Ray Telescope (0.5 Meter) - This telescope has approximately a 16: 1 magnification. Assuming a maximum system sensitivity of 0.1 X-ray-cm^{-2}-sec^{-1} and a proportional counter area of 10 cm^2, the maximum sensitivity at the counter is 16 counts-sec^{-1}. For an S/N of 10 and a sensitivity of 4 x 10^{-3} counts/gamma ray (1 Mev) the gamma ray flux at the interference threshold would be 40 photons-cm^{-2}sec^{-1}; as the proportional counter allows some energy discrimination, the threshold flux is raised to 100 photons-cm^{-2}-sec^{-1}. The threshold for neutrons is estimated as 10^3 neutrons-cm^{-2}-sec^{-1}, and for protons and electrons it is estimated as 10 times less than for gamma rays.

FPE 5.4 HIGH ENERGY STELLAR SURVEY

Nuclear Emulsion/Spark Chamber Gamma Ray Spectrometer - This complex experiment has detectors which may be used separately or in concert. Assuming they would be used separately we consider first the Cerenkov counter. Normally this counter is capable of detecting charged particle speed by measuring (with a PMT) the UV light developed in a transparent dielectric traversed by the particle. In this application it may be set to reject the light from any electron with energy less than 50 Mev, assuming pair production reactions predominate. Thus a proton flux should not produce interference. On the other hand, the high energy photons are assumed to have a flux of the order of 10^{-7} per cm^2-sec. Hence, optics fluorescence by simultaneous, interfering radiations could produce signals mistaken as those from high energy photons. Thus the threshold flux for electrons and protons are set at 10^2 and 10^4 per cm^2-sec, respectively. The neutons flux threshold is conservatively set the same as for gamma rays.

The spark chamber associated with this experiment is capable of considerable energy discrimination by measurement of the discharges due to sparks; however, each discrimination decision disables the counter for a short time ($\sim 10^{-4}$ sec.). The background flux is considered to be at the interference threshold when the fractional dead time associated with such decisions is 0.1. For a 10^2 cm^2 chamber and unity 1 Mev gamma ray interaction probability the interference flux is 10 gamma rays $-cm^{-2}-sec^{-1}$. Similarly, the interaction probability is estimated at 0.1 for neutrons, resulting in a threshold flux of 10^2 $n-cm^{-2}-sec^{-1}$. For charged particles it is assumed that an anti-coincidence shield is used, with a 10^{-5} second dead time.

FPE 5.21 INFRARED STELLAR SURVEY

DC Radiometer - This instrument is one of three which will be used alternately at the focus of a 3M telescope for stellar surveys in the 5 - 14 micron range. This work requires cooling of all telescope components and especially the sensor, as any thermally radiated energy is sensed as noise; similarly, the deposition of nuclear energy at the detector represents noise. A Ge: Hg cooled detector has a noise figure of approximately 10^{-10} watts/cm^2; limiting the radiation deposited energy to one half of this value and assuming the detector is thick enough to absorb 1 Mev

electrons leads to threshold fluxes of about 10^2 electrons-cm^{-2} sec and 10^2 protons-cm^{-2}-sec^{-1} (assumes protons lose some energy before the detector). The gamma ray threshold flux is estimated to be a factor of 20 higher and the neutron threshold flux is estimated to be 2×10^4 n-cm^{-2}-sec^{-1}; better estimates would require detailed considerations of the surrounding materials.

DISCIPLINE: PHYSICS

The FPE's in this discipline cover a variety of experiments, but the sensitive detectors are generally of the types discussed above and the threshold flux values are estimated by similar methods.

DISCIPLINE: EARTH SURVEYS

The FPE's in this discipline generally view the earth and hence receive strong electromagnetic signals; among the more sensitive experiments, however, some are concerned with fine variations in signals which describe small temperature differences. Methods similar to those above are used for threshold estimations. It is noted that data on some experiment gains was lacking and this data would influence the threshold estimations.

DISCIPLINE: ADVANCED TECHNOLOGY

The FPE's in this discipline use a variety of TV and other optical detection systems; the sensors are similar to those described in the Astronomy Discipline.

DISCIPLINE: BIOMEDICAL, BIOSCIENCE

The only radiation interference sensitive components identified in these disciplines are TV cameras and radiation detectors associated with radiobiological tracer studies.

DISCIPLINE: CHEMISTRY, SPACE MANUFACTURING

No dynamic radiation interference was identified in these disciplines.

A.3.3 RADIATION EFFECTS THRESHOLDS--EXPERIMENT SUMMARIES

This section is comprised of 7 charts (Table A-6) which summarize the radiation thresholds by functional program element (FPE) for each Space Base discipline.

A.3.4 SUPPORTING DATA

A.3.4.1 Radiation Effects In Scientific Instruments

This Section compiles information in the literature on specific radiation effects thresholds, both dynamic intereference and permanent damage commonly associated with scientific instruments. Several of the data tables in this section serve as summary references to the particular experiments previously discussed.

The fundamental modes of interference considered are as follows:

Major: Ionization (and its effects)

Minor: Mass transport

Charge collection

Neutron interactions (leading to ionization)

Since ionization is a principal means of signal collection in various sensors, interference in fact may be due to only those radiations for which proper discrimination is incomplete. As an example, an X-ray sensor cannot discriminate between X-rays from a star or reactor but pointing data may allow discrimination; on the other hand, some X-ray sensors are capable of rejecting signals due to energetic protons (with reduced detection time available for X-ray counting).

Table A-6. Experiment Radiation Sensitivity Thresholds

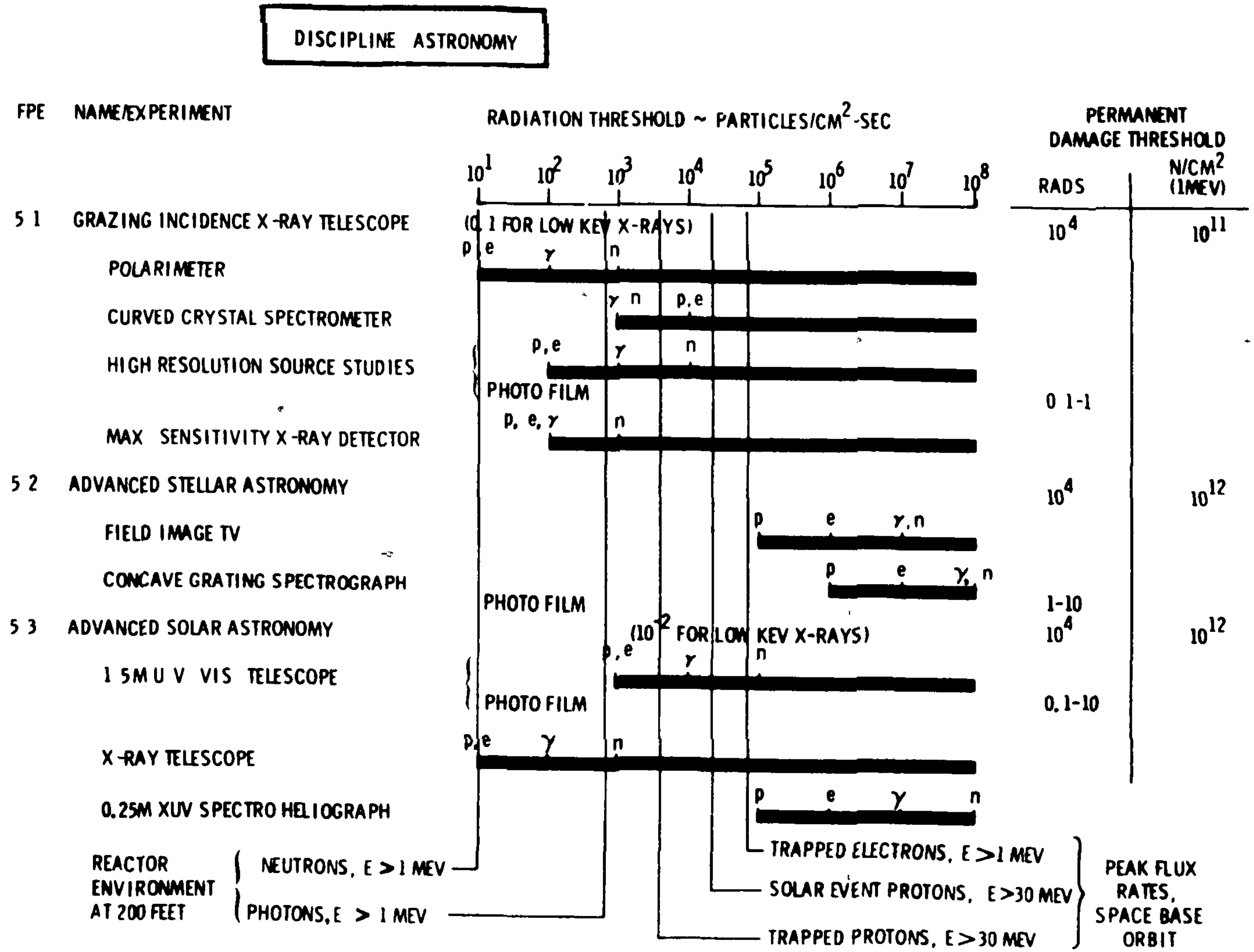

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

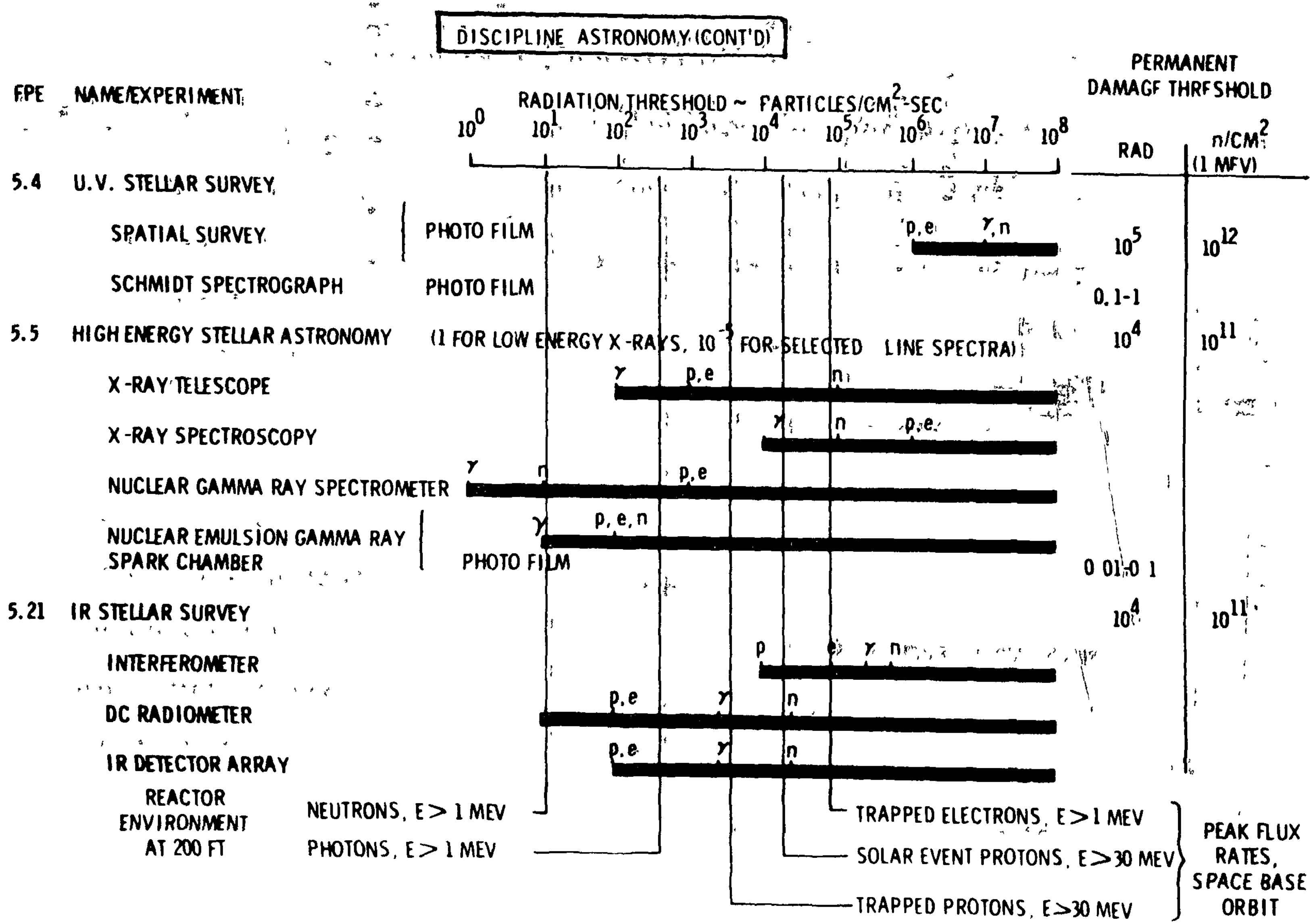

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

DISCIPLINE PHYSICS

FPE	NAME/EXPERIMENT	RADIATION THRESHOLD ~ PARTICLES/CM^2-SEC (10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8)	PERMANENT DAMAGE THRESHOLD RADS	PERMANENT DAMAGE THRESHOLD N/CM^2 (1MEV)
5 6	SPACE PHYSICS AIRLOCK EXPERIMENTS		10^4	10^{12}
	U.V. AIRGLOW	PHOTO FILM	0 1-1	
	GEGENSCHEIN/ZODIACAL LIGHT	p, e γ n		
	CORONAGRAPH CONTAMINATION MEASUREMENT	PHOTO FILM	0 1-10	
	CONTAMINATION MEASUREMENT EXPERIMENT	p, e γ n		
	ENVIRONMENTAL COMPOSITION	p, e γ m		
5.7	PLASMA PHYSICS AND ENVIRONMENTAL PERTURBATION		10^4	10^{12}
	PLASMA WAKE	p, e		
	CYCLOTRON HARMONIC RESONANCE	PHOTO FILM	0.1-1	
	ACCELERATOR EXPERIMENT	p, e γ n		
	PLASMA JET	PHOTO FILM	0.1-10	
5 8	COSMIC RAY PHYSICS LABORATORY		10^4	10^{12}
	INTERACTION PHYSICS	p, e γ n; PHOTO FILM	0 01-0.1	

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

DISCIPLINE ADVANCED TECHNOLOGY

FPE	NAME/EXPERIMENT	RADIATION THRESHOLD ~ PARTICLES/CM^2-SEC (10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8)	PERMANENT DAMAGE THRESHOLD RADS	PERMANENT DAMAGE THRESHOLD N/CM^2 (1MEV)
5.17	CONTAMINATION MEASUREMENTS		10^4	10^{12}
	SKY BACKGROUND BRIGHTNESS	p, e γ n		
	PARTICLE SIZE, DISTRIBUTION	p e γ n		
	CLOUD COMPOSITION	p, e γ n		
	OPTICAL SURFACES DEGRADATION	p e γ n		
	CONTAMINATION DISPERSAL MEASUREMENTS	PHOTO FILM	1-10	
5.18	EXPOSURE EXPERIMENTS		10^4	10^{12}
	IMPACT FLASH SPECTROMETER	PHOTO FILM	1-10	
	METEOR FLASH ANALYZER	p e γ n		
5.20	FLUID PHYSICS IN MICROGRAVITY		10^5	10^{12}
	VARIOUS EXPERIMENTS	PHOTO FILM	1-100	

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

DISCIPLINE: ADVANCED TECHNOLOGY - CONT'D

FPE	NAME/EXPERIMENT	RADIATION THRESHOLDS ~ PARTICLES/CM^2-SEC	PERMANENT DAMAGE THRESHOLDS RADS	PERMANENT DAMAGE THRESHOLDS N/CM^2 (1MEV)
5.22	COMPONENT TEST AND SENSOR CALIBRATION		10^4	10^{11}
	MICROWAVE SETUP			
	LWIR SETUP			
	VARIOUS EXPERIMENTS	PHOTO FILM	1-100	
5.24	ENGINEERING AND OPERATIONS		10^4	10^{12}
	GUIDANCE			
	OPTICAL RADAR			
	LASER COMMUNICATION			

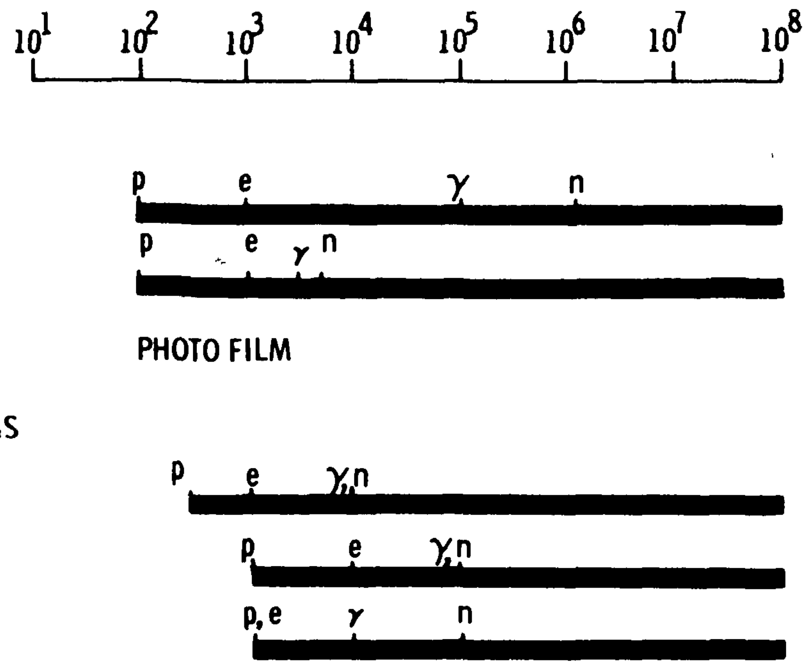

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

DISCIPLINE: EARTH SURVEYS

FPE	NAME/EXPERIMENT	RADIATION THRESHOLDS ~ PARTICLES/CM^2-SEC (10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8)	PERMANENT DAMAGE THRESHOLD: RADS	PERMANENT DAMAGE THRESHOLD: N/CM^2 (1MEV)
5.11	EARTH SURVEYS		10^4	10^{11}
	METRIC CAMERA	PHOTO FILM	0.1-50	
	MULTISPECTRAL CAMERA	PHOTO FILM		
	MULTISPECTRAL IR SCANNER	p, e γ n		
	RADAR IMAGER	PHOTO FILM	0.1	
	VISIBLE WAVELENGTH POLARIMETER	p, e γ n		
	ABSORPTION SPECTROMETER	p, e γ n		
	U.V IMAGER/SPECTROMETER	PHOTO FILM; p, e γ n	1-50	
	PHOTO-IMAGING CAMERA	p e γ n		
5.12	REMOTE MANEUVERING SUBSATELLITE		10^4	10^{12}
	PLASMA WAKE EXPERIMENT	p e γ n		

Table A-6. Experiment Radiation Sensitivity Thresholds (Cont'd)

FPE	NAME/EXPERIMENT	RADIATION THRESHOLDS ~ PARTICLES/CM^2-SEC (10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8)	PERMANENT DAMAGE THRESHOLD RADS	PERMANENT DAMAGE THRESHOLD N/CM^2 (1MEV)
	DISCIPLINE BIOMEDICAL	NON-BIOLOGICAL DATA		
		P e γ, n		
5 13	BIOMEDICAL AND BEHAVIORAL RESEARCH	VIDEO	10^4	10^{12}
5.14	MAN-SYSTEM INTEGRATION			
5.15	LIFE SUPPORT AND PROTECTION SYSTEM	PHOTO FILM - 1-100 RADS		
	DISCIPLINE BIOSCIENCE	NON-BIOLOGICAL DATA		
5 9	SMALL VERTEBRATES	PHOTO FILM 1-100 RADS	10^4	10^{12}
5 10	PLANT SPECIMENS	PHOTO FILM 1-100 RADS		
5.25	MICROBIOLOGY	PHOTO FILM 1-100 RADS		
		P, e γ n		
5.26	INVERTEBRATES	PHOTO FILM - 1-100 RADS		
	DISCIPLINE CHEMISTRY		10^4	10^{12}
5 27	PHYSICS AND CHEMISTRY LAB	PHOTO FILM	1-100	
	DISCIPLINE SPACE MANUFACTURING		10^4	10^{12}
5.16	MATERIALS SCIENCE AND PROCESSING	PHOTO FILM	1-100	

The Space Base experiments have various inherent signal and noise levels and consequently nuclear radiation interference will not be sensed until it attains some appreciable fraction of those levels. Thus, little literature was recovered in the area of interference in TV camera systems where TV has been used for qualitative bright light (strong signal) applications while various planned Space Base uses of TV in dim light have lower signal levels which could be comparable with noise (fog) from nuclear radiations.

A. 3. 4. 2 Interference Data Base

The data base on interference by background nuclear radiations (as found in the literature) comes from three categories: experiment, analysis (i. e. calculation) and flight experience. This data base is helpful but incomplete as it is concerned with only several of the areas of background radiations and experiment types associated with the Space Base. (e. g. little is said about reactor spectra or high energy physics experiments).

Prior experiment data, using RTG's or other radiation sources has been found in references A. 3. 2, 4, 6, 7, 8, 9, 13, 17, 18, 21b, 21c, 21e, 21f, 25, 30, 31, 34, 36. This data covers spurious noise in various sensors as well as radiation induced fluorecence in glasses.

Prior analysis data, usually for RTG or Van Allen belt radiations environments has been found in references; A. 3. 5, 8, 9, 12, 13, 19, 21b, 21d, 33.

Published flight data showing that radiation interference degraded mission success does not describe all the flight data facts. As an example, experimenters probably have turned off equipments during solar flares or simply ignored data attributed to interference and have still collected quality data to meaningfully accomplish objectives. Flight data showing interference, has been found in references A. 3. 6, 7. Also, by personal communication, Mr. N. B. Koepp - Baker of the General Electric Company reported (8/7/70) that the Nimbus Back Scatter UV experiment using PMT's has the signal of its internal radioactive source (used in an interferometer) "bucked out" on each transit of the South Atlantic anomaly region (at $\sim$ 600 nm).

A.3.4.3 Interference Data

Review of the literature on interference quickly allows classification of various sensors. Sensors are most important as noise is most readily introduced at this first stage of data handling. Table A-7 illustrates the sensitivity of various sensors to spurious nuclear radiation. Typically it is noted that only direct radiation sensors fall in the sensitive category. The insensitive category contains those sensors which either have no internal signal gain or are so designed as to only sense non-nuclear radiation quantities such as magnetic field intensity, low energy-charged particle flow, etc. The intermediate category contains those sensors which may be sensitive, dependent upon their internal gain, application, system (or experiment) gain and inherent noise levels associated with their use in an experiment. Consequently their interference thresholds are more difficult to assign.

Table A-7. Typical Sensor Classification (Sensitivity to Spurious Nuclear Radiation)

SENSITIVE	INTERMEDIATE	INSENSITIVE
PHOTOMULTIPLIER TUBES	VIDICONS	LANGMUIR PROBES
ION CHAMBERS	IMAGE ORTHICONS	RF IMPEDANCES
PROPORTIONAL COUNTERS	PLASMA PROBES	FARADAY CUPS
CHANNEL ELECTRON MULTIPLIERS	RADIOMETERS	MAGNETOMETERS
CERENKOV DETECTORS		GRAVIOMETERS
GEIGER TUBES		BOLOMETERS
SCINTILLATION CRYSTALS		PRESSURE TRANDUCERS

One of the most extensive investigations of interference in radiation sensors is reported in Reference A.3.9. This data is summarized in Table A-8. The radiation source was a bare SNAP-27 capsule (which emits energetic gamma rays and neutrons in the approximate ratio of 50:1). Some of the more recent references present data on sensitivity to monoenergetic gamma rays which is consistent with that above. Jones, et all (ref. 21f) report data on interference effects from 0.2 - 0.73 Mev monoenergetic neutrons. Detection efficiencies were on the order of $1\text{-}5 \times 10^{-4}$ for a variety of silicon semiconductor radiations detectors of 30-1000 μ thickness (surface barriers and lithium-drifted types).

Table A-8. Interference - Radiation Sensors

Radiation Sensor	Gamma Ray Response: Counts/Kev / Photon	Gamma Ray Response: Counts / Photon
Proportional counter (Harshaw G-15 at 0.1 Mev)		3.7×10^{-4} x Detector area (cm^2)
Geiger-Mueller Tube (Eon 7302)		2×10^{-3} x Detector Area (cm^2)
Cherenkov Counter (1.5 in dia., 1 cm thick, Peak rate per 20 Kev channel)		5×10^{-4}
Semiconductor Telescope (1 μs gate, false coincidence rate)		1.9×10^{-4}
Channeltron (Bendix CEM4028, saturated mode, above 0.2 Mev)		2.7×10^{-4}
Plastic Scintillators (1.5 in. dia. 1 cm thick, at 1 Mev)	2.5×10^{-6}	
Cesium Iodide (1.5 in. dia., 1 cm thick at 1 Mev)	5×10^{-6}	
Sodium Iodide (1.5 in. dia. square cylinder at 1 Mev)	5.3×10^{-5}	
Silicon Semiconductor Detector (2 mm thick, 1 cm^2 area) @ 1 Mev	6×10^{-7}	
Photomultiplier Tube (RCA 4440, at 50 Kev)	4×10^{-8}	

Interference in optics experiments may originate either in the transmission optics (lenses, windows, etc.) or in the sensor. Table A-9 presents some typical data from the literature on light sensitive tubes and glass fluorescence. No direct data was found on image orthicons or vidicons. However, vidicon tubes normally have a "memory" effect such that the output is a time integral of signal and noise; since the signal is usually steadier than the interference noise, equal light illumination of the photo cathode due to picture image and interference radiation usually produces an acceptable signal to noise ratio. Some low-light applications of vidicons can be sensitive. However, if strongly fluorescing optics are used; image orthicons, in general can be expected to have interference susceptibility between that of photomultiplier tubes and vidicons.

Table A-9. Interference - Optics

Component	Flux or Dose Rate	Output	Reference
Photomultiplier tube (6097S)	0	3×10^{-10} amp	2
	0.01 Rad/Hr	5×10^{-10} amp	2
	0.1 "	2×10^{-9} amp	2
	1 "	1.9×10^{-8} amp	2
	10 "	2×10^{-7} amp	2
Image Dissector Tube (CBS Lab C1-1147)	1.0 Rad/hr	6×10^{-7} amp	13
	10 "	7×10^{-7} amp	13
		Relative Fluoresence ($1600 < \lambda < 6590$ Å)	
Sapphire	6×10^{6} e/cm^2-sec (1.2 Mev)	6.0	7
Spectrosil	"	3.3	7
Corning 9741	"	5.8	7
Cultured Quartz	"	3.3	7

A.3.4.4 Permanent Damage Thresholds

A.3.4.4.1 Photo Film

Photo film is the term used here to describe photographic film as well as various photographic, nuclear dosimetry and nuclear research emulsions. Photo film, apart from special radiation detectors and a limited class of biological specimens, is perhaps the most sensitive material to be subjected to the space/reactor radiation environment. Photo film is also a preferred and logical media for data collection in many experiments. The effects of nuclear radiation background on film are twofold as shown in Figure A-9. The first effect is to increase the background fog density, generally through direct ionization effects as in optical image production by light. The second is to change the slope of the response curve. Thermal neutrons can also cause activation of silver atoms in photo films, leading to delayed ionization effects.

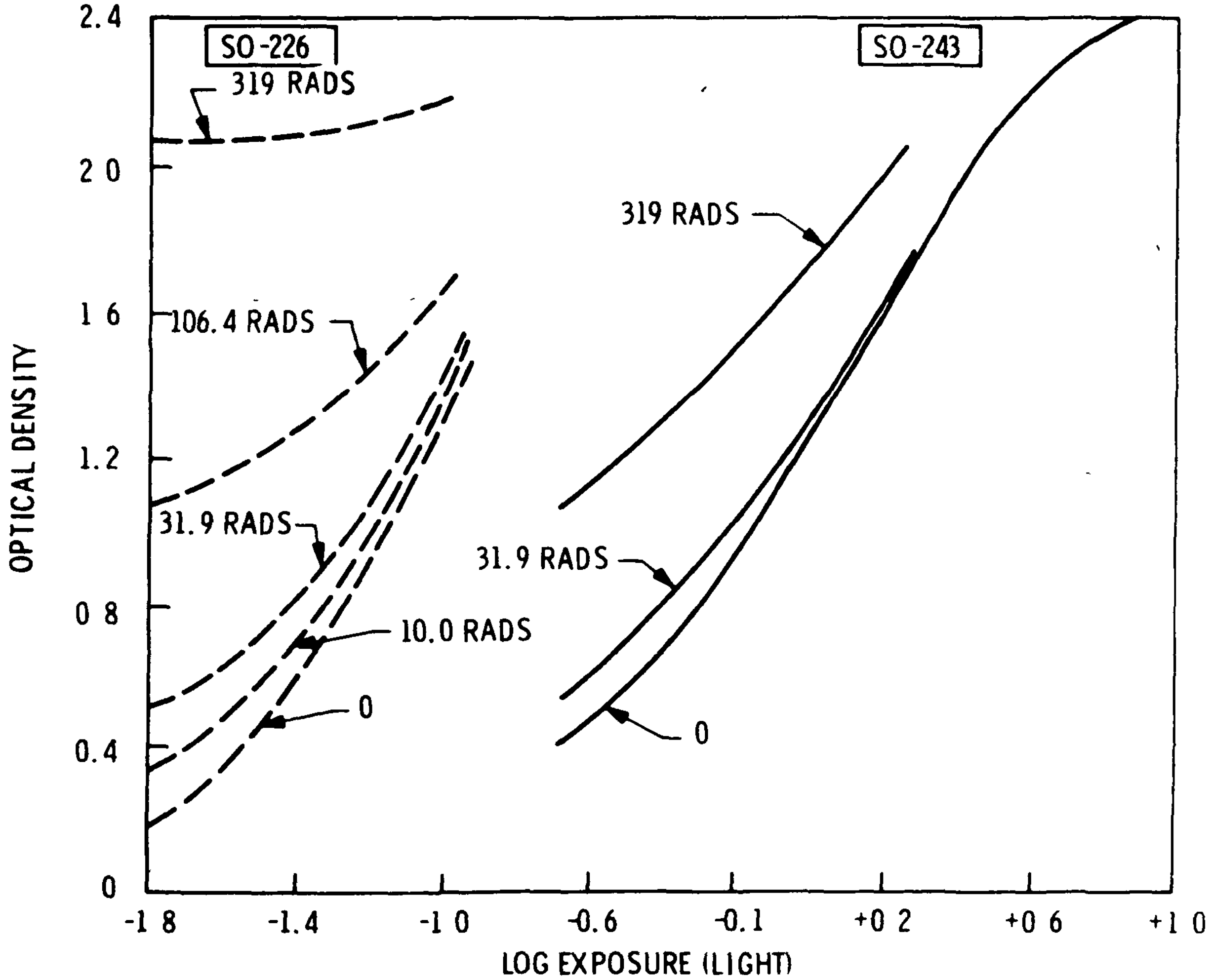

Figure A-9. Photographic Film Response Change with Radiation

The threshold radiation dose for degraded film utility, due to increased background fog is strongly relatable to the inverse of the film speed (ASA number). Thus the faster films are more sensitive to nuclear radiation and constraints on their use for space missions are more severe (shielding, time in orbit, etc.). Table A-10 lists threshold doses on the various photographic film and emulsions uncovered by literature search (together with reference citations). The threshold is defined as that dose for which the net optical density change is 0.2 (some workers in the field use a criterion of 0.3). The threshold doses are clearly low enough in many cases as to require major compromises in design, application and logistics as well as film manufacture and processing.

In the case of film or emulsion used for recording of line spectra there is some discussion in the literature as to a higher threshold dose being allowable, in the area of an optical density of 0.5

Standard references are available which relate various nuclear radiation environments to the absorbed doses in film; for purposes of illustration, the next figure (Figure A-10) describes, for several standard environments, the threshold fluence corresponding to threshold doses for a range of film speeds (shown are Tri-X and Kodak 4404 films).

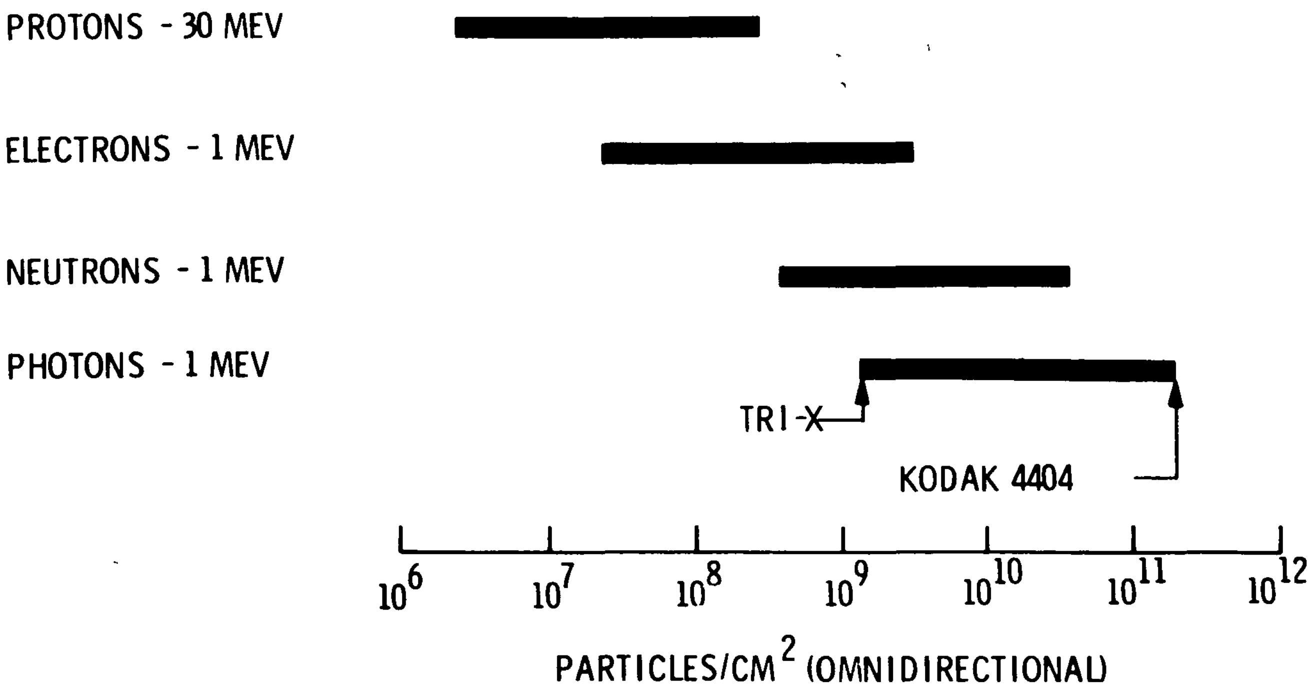

Figure A-10. Photographic Film Degradation Thresholds

Table A-10. Radiation Degradation Thresholds[1] Photographic Film[2] and Emulsions

DESIGNATION	THRESHOLDS ~ RADS	1-2	2-4	4-8	8-16	16-32	32-64	64-128	REFERENCES
107-POLAROID	▲0 1 RADS								4
TRI-X		▲							3
EKTACHROME AERIAL 8842		▲							3
EKTACHROME ER DAYLIGHT		▲							3
HPS-ILFORD		▲							6
SPECTROSCOPIC 103-0		▲							1,2
HP3-ILFORD		▲							6
PLUS-X AERIAL 3401		▲							2,3
ISOPAN RECORD-AGFA		▲							6
SWR (IMPROVED) SC-7			▲						1
101-01			▲						6
PLUS-X PAN			▲						6
PLUS-X			▲						1,3
KODACHROME 11 DAYLIGHT			▲						3
SC-5			▲						1
SC-5T-KODAK PATHE				▲					6
KB-17 -ADOX				▲					6
KODACOLOR				▲					3
PANATOMIC-X				▲					1,2,3
SWR (SHORT WAVE RADIATION)					▲				1,2,3,6
SO-226-MANUFACTURER UNKNOWN					▲				5
CINE POSITIVE 5302-MANUFACTURER UNKNOWN						▲			3
SC-7T-KODAK PATHE						▲			6
FINE GRAIN AERIAL SO-190							▲		3
SPECIAL SOLAR RECORDING, SO-375							▲		1,2
SO-243-MANUFACTURER UNKNOWN							▲		5
MICROFILE - MANUFACTURER UNKNOWN								▲	3
HIGH DEFINITION AERIAL, 4404								▲	3
SENSITIVE NUCLEAR DOSIMETRY EMULSIONS	▲0.2 RADS								7
SENSITIVE NUCLEAR RESEARCH EMULSIONS	▲0.01 RADS								8

1 THRESHOLD = DOSE FOR Δ O D = 0 2
2 EASTMAN KODAK UNLESS OTHERWISE NOTED

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A.3.4.4.2 Optics

The term optics covers a variety of sources, materials for transmission, focusing and filtering as well as sensors. This section is intended to cover the optics field in sufficient depth to set critical permanent damage limits for use in a radiation environment.

The laser, in some of its forms is noticeably sensitive to radiation. The following summarizes data on ruby lasers (Ref. 8, 9): absorbed doses of 10^4 rads color the ruby and reduce the efficiency of stimulated emission by about 30%, absorbed doses of 10^5 rads raise the threshold for stimulated emission by at least 30% and line width and far-field pattern were unaffected at 10^6 rads.

A great variety of glasses are used as light transmission devices and data in this area is tabulated in Table A-11. The radiation threshold is set at the dose for which transmission in a test sample is degraded by about 5%. The transmission degradation is visible as a browning or formation of color centers and is typically related to the impurity concentration. A common practice in space flight applications is to use a superior glass on the side of a window exposed to space; although the use of reflective optics such as in telescopes avoids most radiation degradation modes. Refractive index changes have been reported for a few optical glasses and is summarized in Table A-12.

Table A-11. Transmission Degradation Thresholds - Glass

DESIGNATION	RADIATION THRESHOLDS - RADS 10^5	10^6		10^7	10^8	10^9	REFERENCES
Borosilicate	X						1
Natural Quartz							1
Visible	X						
Ir				X			
Purified Fused Silica							1
$\lambda > 2200$ Å					X		
$\lambda = 2150$ Å		X					
Silicon Germanium				X			-
Sapphire, Al_2O_3				X			2
MgO				X			2
Selenium Glass			X				2
ArS_3				X			2
Calcium Aluminate			X				2
Vycor 7905							2
Visible		X					
Ir				X			
MgF_2				X			3
BaF_2				X			3
LiF	X						3
Corning 7940						X	4
Solex				X			5
Plate Glass		X					5
Polystyrene			X				6
Plexiglas	X						6
Allycarbonate		X					6

Table A-12. Refractive Index Change, $\Delta\eta$

Glass	Δn	Exposure	Reference
Flint Borosilicate Barium Crown	<0.0002	10^6 Rads plus 10^{15} e/cm^2 (2 Mev)	10
Fused Silica	No appreciable change	10^8 rads plus 10^{15} e/cm^2	10
Fused Silica, 7940	+5 to -12 x 10^{-5}		11
Flint (Ce prot.) Borosilicate (Ce prot.)	<0.00006	10^8 rads plus 10^{15} e/cm^2	10
Aluminosilicate	+9 to +30 x 10^{-5}	A	11
Vycor 7913	+9 to +25 x 10^{-5}	A	11

A - equivalent of 30 days in space, λ from 0.2652 to 2.553 μ

Index changes of the magnitude observed may result in serious degradation of image quality in high resolution lens systems (Ref. 10).

A variety of sensors are used in light detection; these include photomultiplier tubes, bolometers and TV cameras. The degradation threshold data are summarized in Table A-13.

Table A-13. Typical Optical Sensor Degradation Thresholds

Sensor	Dose for Permanent Damage Threshold N/Cm^2	Dose for Permanent Damage Threshold Rads	Reference
Photomultiplier Tube	10^{12}	10^5	1
Photo Tube	10^{12}	3×10^5	1
Vidicons	10^{12}	3×10^5	1
Image Orthicons	10^{12}	3×10^5	1
IR Detector			
PbS (135 °F)	10^3	-	12
PbSe (135 °F)	2×10^{13}	-	13
Thermistor-Bolometer	4×10^{13}	-	14

A.3.4.4.3 Radiation Sensors

As with electronic circuitry, the most easily damaged radiation sensors are those employing semiconductors. Radiation sensors employing metals, gases and ceramics are usable to high radiation fluences. Table A-14 presents degradation data for various sensors.

Table A-14. Permanent Damage Thresholds - Radiation Thresholds

Radiation Sensor	Exposure Environment	References
Silicon (Surface barrier) Diffused Junction	10^{10} p/cm^2, E ~ 5-10Mev 10^{12}-10^{13} e/cm^2, E ~ 2-5 Mev > 10^7 R, gamma rays 10^{11}-10^{12} n/cm^2, E ~ 1 Mev 10^9 α/cm^2, E ~ 5-50 Mev	32
Silicon (lithium drifted) Detector	10^7-10^8 p/cm^2, E ~ 5-10 Mev 10^4 R, gamma rays 10^{10} n/cm^2, E ~ 1 Mev 10^7 α/cm^2 E ~ 5-50 Mev	32
Fission Chamber Ion Chamber	10^{18} n/cm^2, E ~ few Mev	29
Scintilon Photo multiplier Tube	10^{12} n/cm^2 (E > 0.1 Mev) + 2×10^3 rads 10^{12} n/cm^2	18

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A.4 RADIATION EFFECTS ON SPACE BASE BIOLOGICAL EXPERIMENTS

A.4.1 GENERAL

In most cases the organisms contained on a Space Base for bioscience experiments are more radioresistant than man. However, for certain stages of development and for particular tissues, radiosensitivity among animals and plants can be rather high. An example of an organism in which a wide range of resistance is seen is the fruit fly. The adult fly has an LD_{50-1} (dose required to kill 50% in one day) of 60 to 200 kilorads depending on age, while the LD_{50} of fruit fly eggs is less than 200 rads. Other examples are given in the following section. In addition to stage sensitivity, cyclic sensitivity has been shown (Ref. A.4-1) in frog embryos. Resistance appeared to be a direct function of DNA content since the greatest sensitivity was at telophase/early interphase and the greatest resistance occurred at late interphase. A similar radiosensitivity based on DNA content (chromosome volume) has been shown by Sparrow and co-workers (A.4-2). For different spheres, however, radiosensitivity appears to be a direct function of chromosome volume (see Figure A-11 and the following Section). These data plus other specific and extrapolated information allow estimates of experiment radiosensitivity of a range of biological specimens as shown in Figure A-12. It has been assumed that Space Station Experiments as given in the NASA Blue Book would typify those experiments to be performed on a Space Base. The wide range in sensitivities shown for some species is due to the variety of tissues or developmental stages to be studied.

Also shown are preliminary estimates of the natural trapped radiation dose for a 30-day period for a range of shield thickness from 1 g/cm^2 to 10 g/cm^2 (Ref. A.4-3). Also shown for comparison, is the estimated 30-day dose from the reactor source at the (60m 200 ft) dose plane. As can be seen, the natural trapped environment poses the more severe problem. In addition, the dose from a single solar flare could range from about 470 rads for 1 g/cm^2 shielding down to about 30 rads for 10 g/cm^2 shielding (Ref. A.4-3).

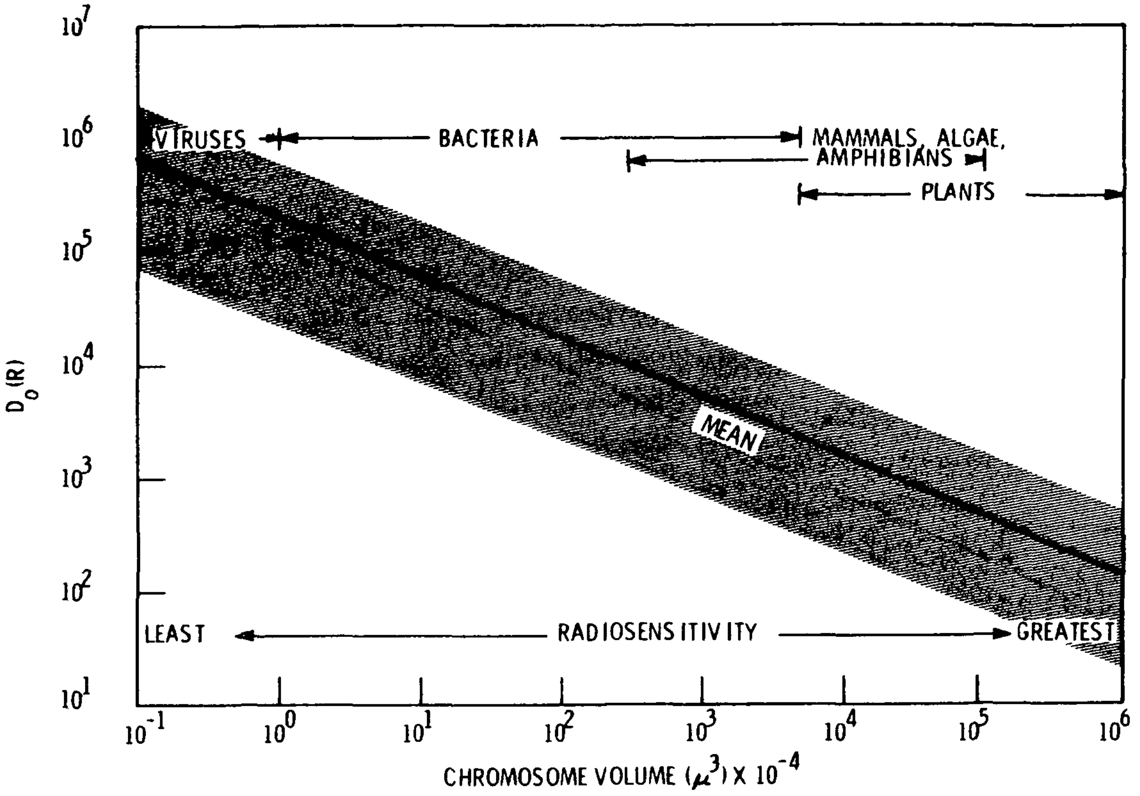

Figure A-11. Relationship of D_o and Chromosome Volume

A.4.2 ACUTE RADIATION EFFECTS

Mammals other than man generally are somewhat more resistant to radiation than man. This is also true of the lower vertebrates (Table A-15). Invertebrates have a high radiation tolerance - usually measured in thousands of rads. Mature plants are also quite resistant. The data given in Table A-15 should be taken as "ball park" in that they may differ with radiation quality, dose protraction and dose distribution. An example of the latter is given in Table A-16.

Table A-15. Median Lethal Doses for Animals

	DOSE IN RADS
VERTEBRATES	
MAN	300
MONKEY	530
DOG	300
GUINEA PIG	250
RABBIT	800
RAT	750
MOUSE	625
CHICKEN	900
FROG	850
SALAMANDER	1,000
MEXICAN AXOLOTL	1,400
NEWT	1,500-2,500*
MUD PUPPY	3,550
TURTLE	1,100
SNAKE	350
GOLDFISH	670
INVERTEBRATES	
FRUIT FLY	60,000-200,000**
AMOEBA (PELOMYXA)	80,000
E COLI	20,000
BREAD MOLD (NEUROSPORA)	12,000

*DEPENDING ON SPECIES
**DEPENDING ON AGE LD_{50-1}

EXPERIMENT CATEGORY	SPECIMEN	TYPICAL EXPERIMENTS
ANIMALS	VERTEBRATES	
	CHIMPS	METABOLISM, CARDIOVASCULAR, CNS
	MONKEYS	METABOLISM, BEHAVIOUR, CARDIOVASCULAR, CNS
	RATS	EMBRYOGENESIS, GROWTH, METABOLISM
		BEHAVIOUR, CIRCULATION, BIORHYTHMS
	MICE, HAMSTERS, RABBITS	EMBRYOGENESIS, GROWTH, METABOLISM
	MARMOTS	IMMUNE RESPONSE
	FROGS	EMBRYO AND DEVELOPMENT
	TURTLES	GROWTH AND METABOLISM
	INVERTEBRATES	
	FRUIT FLY	LIFE CYCLE, GENETICS
		METABOLISM, BIORHYTHMS
	HOUSE FLY	AGING
	FLOUR BEETLE	MOIPHOGENESIS
	BEES AND SPIDERS	BEHAVIOUR
PLANTS	WHEAT	GROWTH
		METABOLISM AUXIN
	PEA	GROWTH
	ARABADOPSIS	DEVELOPMENT
	P. LONGFOLIA	METABOLISM, MORPHOGEN, FERTILIZATION
	CUCUMBER	LIGNIFICATION
	PINTO BEAN	BIORHYTHM
MICROBIOLOGICAL	VERTEBRATES	TISSUE FUNCTION
	AVIAN	EMBRYO DEVELOPMENT
	VIRUS BACTERIA	HOST PARASITE
	FUNGI	BIORHYTHM
	CELL	CELLULAR FUNCTION
		METABOLISM
	GENES	GENETIC STABILIZATION

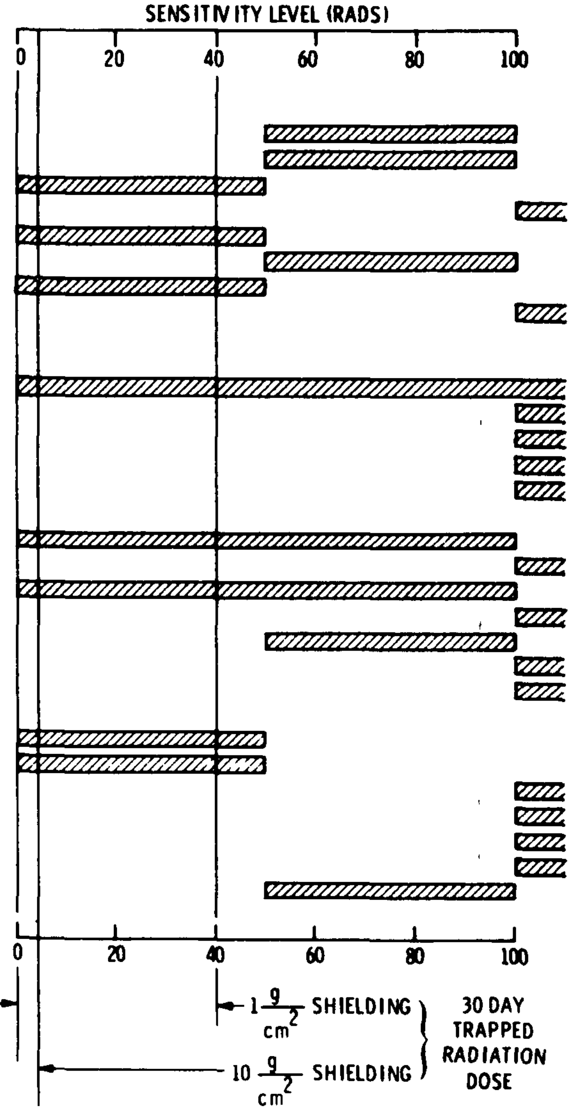

Figure A-12. Bioscience Experiment Radiation Sensitivity

Table A-16. Variation in LD_{50} with Body Region and Volume Exposed

SPECIES	EXPOSURE CONDITIONS	EXPOSURE (R or rads)	INTEGRAL DOSE (kg-rads)
Rats	^{60}Co gamma rays, whole body uniform	830	170
	^{60}Co gamma rays, whole body (midline dose 25 percent of surface dose)	2,590	260
Rats	X rays, whole body uniform	700	175
	X rays, abdomen shielded	1,950	275
	X rays, abdomen irradiated, rest shielded	1,025	134
Rats	X rays, whole body	750	150
	X rays, upper body	1,750	130
	X rays, lower body	1,080	136
Dogs	X rays (250-kVp), whole body	275	2,250
	X rays (250-kVp + 50-kVp), whole body	1,226	2,580
	X rays (250-kVp + 50-kVp), whole body	3,205	3,880
Dogs	X rays (1,000-kVp), whole body	250	2,500
	X rays (1,000-kVp), upper 54 percent of body	1,775	9,600
	X rays (1,000-kVp), lower 46 percent of body	855	3,900
Monkeys	Protons (400-MeV), whole body	585	—
	Protons (138-MeV), whole body	516	—
	Protons (55-MeV), whole body	~1,150	—
	Protons (32-MeV), whole body	1,600	—

In general, the most radioresistant tissues are those that are rapidly dividing such as hematopoietic and germinal tissues. As is the case with most generalities, however, there are exceptions. For example, with the onset of mitosis, germinating wheat seedlings become more resistant to the growth retarding effect of X radiation and the sensitivity of fruit fly eggs does not exactly parallel the rate of division.

A.4.3 NON-LETHAL EFFECTS

Since most of the experimental organisms to be used on a Space Base are more radioresistant than man, and man is of primary interest in any safety study, it is perhaps of more relevance to discuss sub-lethal effects that may invalidate bio-experiments concerning weightlessness. Some of these effects for various radiation levels are given in Table A-17. A recently discovered (Ref. A.4.4) example of high radiosensitivity involves altered behavior in the rhesus monkey. Sixty (60) mr/sec of x-rays directed to the head is sufficient to cause an immediate alteration in bar pressing behavior. A six minute lag is required for 6 mr/sec, and the threshold for response is 4 mr/sec.

Table A-17. Sublethal Radiation Effects

BIOLOGICAL SPECIMENS TEST MATERIAL	RADIATION IN RADS	EFFECT OBSERVED
GRASSHOPPER (NEUROBLAST)	8	DECREASED RATE OF MITOSIS
FROG (SPERM)	15-500	ABNORMAL DEVELOPMENT (5-100%)
MOUSE (TESTIS)	20-600	DAMAGE TO GERMINAL CELLS
MOUSE (THYMUS)	30-800	WEIGHT LOSS
MOUSE (SKIN)	35-225	CELLS IN MITOSIS DECRFASED
RAT (RETINA)	36-540	INHIBITION OF MITOSIS
SALAMANDER EGGS	50	LD_{50}
BLUEBOTTLE FLY (EGGS)	50-110	LD_{50}
CHICK (FIBROBLAST CULTURE)	100	DEATH OF CELLS AT NEXT DIVISION
FROG (EGGS, FERTILIZED)	100-1000	ABNORMAL DEVELOPMENT
GRASSHOPPER (EGGS, 1 DAY OLD)	125	LD_{50}
BROAD BEAN (ROOT)	140	INHIBITION OF GROWTH
FRUIT FLY (EGGS)	190	LD_{50}
THYMUS (CELL SUSPENSION)	200	DEATH OF CELLS
PINE TREE (P STROBUS)	275	SEVERE GROWTH INHIBITION

The principal site of damage to plants (as is the case with animals) by ionizing radiation is the cell nucleus. The effect on plant growth can vary considerably. The pine tree P. strobus is about 500 times more sensitive than other higher plants. The main reasons for this large difference is the large nuclear volume of pines and for chronic exposures, the long period between production of the meiocytes and the maturation of the seed. A linear relationship between nuclear volume and dose (log-log plot) has been shown (Ref. A.4.5). Aradibopsis which has a nuclear volume of 23 μ^3 is quite resistant, while Tradescantia with a volume greater than 1,000 μ^3 shows a severe growth inhibition. In addition, Sparrow and Miksche (Ref. A.4.5) have shown a relationship between the total amount of DNA per diploid nucleus and sensitivity. A better correlation, however, is shown between sensitivity and DNA quantity per chromosome.

More recent studies of Sparrow and co-workers (Ref. A.4.6) in which 79 different organisms were compared corroborate the previous finding of a direct relationship between radiosensitivity and chromosome volume as shown in Section A.4.6.

Data from both plants and animals indicate that increasing degrees of ploidy confer increasing degrees of resistance to radiation damage. There are exceptions to this as in yeast and at certain stages of development of the parasitic wasp (Habrobracon). In addition to ploidy, there is a fair amount of evidence that in diploids an increasing chromosome number (or number of chromosome arms) has protective value. The above generalizations plus information on the type and quality of radiation and dose protraction allow calculations of sensitivity in organisms that have not been irradiated previously.

A.4.4 RADIATION QUALITY

Examples of the relationship of biological effect to radiation energy is given in Table A-18 for mouse spermatogonia and oocytes, Table A-19 for breadmold and Table A-20 for human leukocytes.

Table A-18. RBE of Proton to X-Rays and 14.1-MeV Neutrons to Co^{60} γ-Rays for Spermatogonial and Oocyte Killing

Radiation	Cell type	RBE		
		Lower 95% confidence limit	Point estimate	Upper 95% confidence limit
	Spermatogonia:			
14.1-MeV neutrons[a] ----	A-----------	1.41	1.76	2.76
	Late A------	2.19	2.52	2.89
	Late A + In--	2.11	2.38	2.69
	Spermatogonia:			
130-MeV protons-------	A-----------	0.28	0.47	0.70
	Late A-------	0.41	0.64	0.95
	Late A + In --	0.27	0.68	1.40
	Oocytes------	0.00	0.28	0.73
	Spermatogonia:			
750-MeV protons-------	A------------	0.64	0.84	1.10
	Late A-------	0.52	0.77	1.11
	Late A + In---	0.69	0.96	1.34
	Oocytes-------	0.20	0.66	1.53

[a] From Oakberg and Clark, 1961. (Ref. A.4.7)

Table A-19. RBE's for Cellular Inactivation and Mutation in Neurospora (After DeSerres and Webber, 1963) (Ref. A.4.9)

Radiations	Cellular inactivation: Inactivation coefficients[a]	Cellular inactivation: RBE	Mutation: RBE for ad-3R mutation (one-hit)	Mutation: RBE for ad-3IR mutation (two-hit)
750-MeV protons ------	0.1145	1.77	1.36	1.47
447-MeV protons------	0.0675	1.02	0.87	1.00
442-MeV protons------	0.0839	1.30	1.24	1.30
250 kVp X-ray--------	[b]0.0648	1.00	1.00	1.00
39-MeV helium ions---	0.105	1.62	2.37	1.81
101-MeV carbon ions--				

[a]The inactivation coefficients are the reciprocals of the medium lethal dose (e^{-1}) in kilorads.

[b]Average of inactivation constants from four experiments is used for 250-kVp X-ray inactivation constant.

Table A-20. Coefficients of Chromosomal Aberration Production for Proton Irradiation of Human Leukocytes

(After Bender & Gooch, 1962) (Ref. A.4.10)

Radiation	Coefficient of aberration production: Deletions [a]	Coefficient of aberration production: Rings and dicentrics [b]	RBE [c]
750-MeV protons	0.6×10^{-3}	6.0×10^{-6}	0.7
450-MeV protons	0.9	5.5	1.0
130-MeV protons	0.9	6.0	1.0
100-MeV protons	0.7	5.3	0.8
50-MeV protons	0.4	5.8	0.4
250-kVp X-rays	0.9 ± 0.03	6.0 ± 0.5	[d] 1.0
14-MeV neutrons	2.3 ± 0.2	(e)	2.6
2.5-MeV neutrons	2.8 ± 0.2	(e)	3.1
1-MeV neutron	5.0	(e)	5.6

[a]From $Y = a + bD$; the coefficient is b, expressed in aberrations/cell/rad.
[b]From $Y = cD^2$; the coefficient is c, expressed in aberrations/cell/rad^2.
[c]Calculated from deletion coefficient only.
[d]By definition.
[e]For purposes of comparison, these coefficients would be meaningless because the kinetics of two-hit aberration production change in this LET range, becoming approximately linear for 2.5 MeV neutrons.

Underbrink and co-workers (1970) (Ref. A. 4. 8) have shown a wide range of RBE's for various mutations in the wild blue flower (Tradescantia). With dose ranges of 0.163 to 24.4 rads for 0.43 MeV neutrons and 11.5 to 432 rads for x-rays the following mutations were noted:

Mutation	RBE
Blue Dwarf	23.5
Pink	30.7
Colorless	39.1
Blue Giant	120.5

A. 4. 5 EFFECTS ON BIOLOGICAL COMPOUNDS

A Space Base undoubtedly will be well stocked with various compounds to be used in the conduct of experiments. Table A-21 gives the effects of radiation on some of these compounds.

A. 4. 6 RADIOSENSITIVITY AND CHROMOSOME VOLUME CORRELATION

The following data, Table A-22, have been assembled by Sparrow and co-workers (Ref. A. 4. 5). Cellular radiosensitivity (D_o) has been computed from the e^{-1} survival point, i.e., 37% survival. When the survival curve is exponential as for viruses, one ionization on or very near the target is sufficient to inactivate the target, and D_o corresponds to the dose required to score an average of one hit per target. A radiotaxon is a regression group in which the energies absorbed per chromosome at D_o are similar.

Correlation between D_o and chromosome volume are shown in Figure A-13. Points fitted to slopes = -1. Chromosome volumes were multiplied by 10^4 to facilitate computing data. The arrow indicates position at which chromosome volume equals one cubic micron ($1 \mu^3$).

Table A-21. Ionizing Radiation Effects: Biologically Important Compounds[1]

d = deuterons, e = electrons, n = neutrons, r = roentgens, α = alpha particles, β = beta particles, γ = gamma rays

	Material	Radiation	Dose	Intensity	Effect or Product	Molecules/100 ev
	Acids					
1	$C_nH_{2n+1}COOH$ (n = 1-29)	α (Rn)			CO_2	0 5-2 8
2					CO	<0 5
3					H_2	<0 4
4					H_2O	0 9-2 5
5					C_nH_{2n+2}	0 4-1 1
6	Formic (aqueous)	e (1 4 Mev)			Loss of acid function	2 5
7		d (4 Mev)			Loss of acid function	1 7
8		γ (Co^{60}		5×10^4 r/hr	CO_2	4 1
9					H_2	0 5
10					H_2O_2	4 6
11	Acetic (aqueous deaerated 1 M)[2]	He^{++} (35 Mev)[3]	$3\ 8 \times 10^{20}$ ev/ml	0 2 μa	CO_2	0 28
12					Succinic acid	0 32
13					CH_4	0 08
14		d (18 Mev)	$3\ 8 \times 10^{20}$ ev/ml	0 2 μa	CO_2	0 39
15					Succinic acid	0 59
16					CH_4	0 11
17	Caprylic (liquid)	α (Rn)			H_2 CO_2, CO H_2O, CH_4, C_2H_6, C_3H_8, C_4H_{10}	
18	Lauric (solid)	α (Rn)			H_2 CO_2, CO, H_2O, n-$C_{11}H_{24}$	
19	Palmitic (solid)	α (Rn)			H_2, CO_2, CO, H_2O n-$C_{15}H_{32}$	
20	Glycolic, Ca salt (solid)	β (C^{14})	$1\ 75\text{-}2\ 54 \times 10^7$ r		Decomposition	31-77
21	Oxalic (aqueous)	X (2 5 Mev)	~ 10^6 r		Loss of acid function	4-6
22	Lactic (aqueous)	X	$1\ 2 \times 10^4$ r		Pyruvic acid	
23	Benzoic (aqueous)	X (220 kv)	10^4-10^5 r	2350 r/min	o-$C_6H_4(OH)$ COOH	1 0
24					m-$C_6H_4(OH)$ COOH	
25					p-$C_6H_4(OH)$ COOH	
	Alcohols, Thiols					
26	Methanol (liquid)	β (C^{14})	$5\ 94 \times 10^8$ r		Decomposition	12
27		He^{++} (27 Mev)[3]		$1\ 9\text{-}3\ 9 \times 10^{21}$ ev/sec	H_2	3 4-4 1
28		He^{++} (27 Mev)[3]		$1\ 9\text{-}3\ 9 \times 10^{21}$ ev/sec	HCHO	1 7
29	Ethanol (liquid)	He^{++} (27 Mev)[3]		$1\ 3\text{-}5\ 1 \times 10^{21}$ ev/sec	H_2	1 8-3 2
30					CH_3CHO	0 7-1 7
31					$(CH_2OH)_2$	0 7-1 1
32	Sucrose (solid)	X			Inversion red color	
33	Sucrose (aqueous)	X			Inversion	
34	Propane-1, 3-dithiol (aqueous)	X (250 kv)	500-5000 r		Oxidation	11
35	2,3-Dimercapto-1-propanol (BAL)(liquid)	X (250 kv)	500-5000 r		Oxidation	11
	Vitamins and Related Compounds					
36	o-Aminobenzoic acid (aqueous)	e (3 Mev)			Decarboxylation, loss of amine function	
37	p-Aminobenzoic acid (aqueous)	e (3 Mev)			Decarboxylation loss of amine function	
38	β-Carotene (petroleum ether)	X (3 Mev)	$0\ 66 \times 10^6$ r		Decomposition	0 16
39	Choline chloride (solid)	β (C^{14})	$1\ 07 \times 10^7$ r		Decomposition	490
40	Niacin (aqueous)	e (3 Mev)	$0,17\text{-}5,28 \times 10^6$ r		Decarboxylation	1, 6
	Amino Acids					
41	Glycine (aqueous)	X (200 kv)		3500 r/min	H_2, NH_3, HCHO (trace)	Non-linear
42		X (500 kv)	$1\ 66 \times 10^5$ r		NH_3	≤ 9 1
43		β (n α) Li	$8\text{-}20 \times 10^{20}$ ev/ml		NH_3	≤ 1 7
44	Alanine (aqueous)	X (220 kv)		3500 r/min	H_2, NH_3 CH_3CHO (trace)	Non-linear
45	Serine (aqueous)	X (200 kv)		3500 r/min	H_2, NH_3, $(CHO)_2$ $HOCH_2CHO$	Non-linear
46	L-Serine (aqueous)	X	$1\ 66 \times 10^5$ r		NH_3	1-13
47	Valine HCl (solid)	β (C^{14})	$8\ 2 \times 10^6$ r		Decomposition	0 3
48	Norvaline HCl (solid)	β (C^{14})	$4\ 03 \times 10^7$ r		Decomposition	1 7
49	Norleucine (solid)	β (C^{14})	$3\ 2 \times 10^6$ r		Decomposition	10
50	Cysteine (aqueous)	X (250 kv)		10^3 r/min	Loss of thiol function	6-26
51					H_2O_2	0-7
52					H_2S.	~1 (aerated)
53					H_2S	2 5-5 (deaerated)
54	Histidine HCl (aqueous)	e (3 Mev)	10^5 - 10^6 r		Decomposition	1 0-10
	Steroids					
55	Cholesterol (aqueous)	X (200 kv)		3000 r/min	Cholestane-3(β) 5(α) 6(β)-triol, 3(β)-hydroxycholest-5-en-7-one	
56	Δ^5-Pregnen-3-(β)-ol-20-one (aqueous)	X (200 kv)		3000 r/min	3(β),5(α), 6(β)-Trihydroxyallo-pregnan-20-one	
57	Cholic acid (aqueous)	X (220 kv)	$1\ 8 \times 10^6$ r		3(α) 12(α)-Dihydroxy-7-ketocholanic acid	
58	(+)-Estrone-b (aqueous)	X (200 kv)	10^6 r		A lactone	
	Miscellaneous					
59	Desoxyribonucleic acid (aqueous)	X (200 kv)		3000 r/min	NH_3	0 4
60					Inorganic phosphate	0 003
61	Yeast ribonucleic acid (aqueous)	X (200 kv)		3000 r/min	NH_3	0 4
62					Inorganic phosphate	0 01
63	Sodium thymonucleate (aqueous)	X (0 2 2 Mev)			Decomposition	
64		γ (Ra Co^{60})			Decomposition	~0 06
65	Carboxypeptidase (aqueous)	α (Rn)			Inactivation	0 03
66		X (500 kv)			Inactivation	0 55
67	Ferricytochrome c (aqueous)	X (180-200 kv)		439-1700 r/min	Oxidation	1 7
68	Glutathione (aqueous)	X (250 kv)	500-5000 r		Oxidation	10

/1/ In all aqueous media radiolysis may yield H_2 H_2O_2, and O_2 dependent on conditions, such data are not included here /2/ Data for aerated solution are more complex /3/ Rays of artificial (cyclotron) origin

Table A-22. Chromosome Volumes, D_0's, and Energy Absorption Values per Chromosome at D_0 for 79 Different Organisms

Organism	Code no.	Chrom. no.	Chrom. vol. (μ^3) x 10^{-4}	D_0 (R)	eV/chrom. at D_0
	Radiotaxon I				
Coliphage R17	1	1	0.042	8.4×10^5	211
Coliphage ØX174	2	1	0.075	4.4×10^5	199
Tobacco ringspot virus	3	1	0.093	4.6×10^5	258
Shigella phage S13	4	1	0.082	3.6×10^5	178
St. Louis encephalitis (Hubbard strain)	5	1	0.082	3.4×10^5	170
Poliovirus (Lansing strain)	6	1	0.115	3.4×10^5	238
Western equine encephalitis virus	7	1	0.141	3.0×10^5	255
Tobacco mosaic virus	8	1	0.151	2.9×10^5	259
Coliphage C13	9	1	0.211	1.2×10^5	152
Bacillus megatherium phage -	10	1	0.416	9.0×10^4	225
Bacillus megatherium phage α	11	1	0.970	2.2×10^4	126
Herpes simplex virus	12	1	5.236	6.2×10^3	196
	Radiotaxon II				
Tobacco necrosis virus	13	1	0.109	6.7×10^5	440
Tomato bushy stunt virus	14	1	0.154	4.5×10^5	417
Coliphage C36	15	1	0.388	2.1×10^5	491
Bacteriophage P28	16	1	0.655	9.8×10^4	386
Coliphage T3, T7	17	1	0.871	1.1×10^5	577
Coliphage λ	18	1	0.824	1.0×10^5	496
Salmonella phage P22	19	1	0.871	8.8×10^4	461
Adenovirus type 5	20	1	1.130	7.0×10^4	476
Influenza type A virus	23	1	2.037	5.9×10^4	723
Coli 234-dysentery Y6R phage C16	24	1	1.650	4.1×10^4	410
Influenza type B virus	25	1	2.037	3.7×10^4	454
Coliphage T5	26	1	2.209	3.6×10^4	472
Coli PC phage -("phage PO")	27	1	2.681	4.0×10^4	646
	Radiotaxon III				
Shope rabbit papilloma virus	28	1	0.736	4.4×10^5	1,950
Polyoma T virus	29	1	0.6[illegible]	4.1×10^5	1,517
Potato virus X	30	1	0.684	3.3×10^5	1,358
Coliphage T1	31	1	1.24[illegible]	4.6×10^5	1,954
Fowl plague virus	32	1	2.037	4.0×10^5	1,826
Pseudomonas phage P8	33	1	2.681	8.6×10^4	1,388
Coliphage T2	34	1	5.890	4.6×10^4	1,642
Coliphage T4	35	1	5.890	4.0×10^4	1,418
Bacillus subtilis phage -	36	1	7.455	4.4×10^4	1,975
Shope rabbit fibroma virus	37	1	44.452	8.3×10^3	2,221
Staphylococcus aureus	38	1	59.641	3.9×10^3	1,407
	Radiotaxon IV				
Rous sarcoma virus	39	1	9.0	8.9×10^4	4,848
Vaccinia virus	40	1	18.98	8.8×10^4	10,030
Newcastle disease virus	41	1	19.16	4.7×10^4	5,421
Mycobacterium tuberculosis	42	1	26.88	3.5×10^4	5,663
Diplococcus pneumoniae	43	1	84.09	1.7×10^4	8,606
Sarcina lutea	44	1	107.00	1.7×10^4	10,951
Escherichia coli ("Bact. coli")	45	1	141.37	5.7×10^3	4,851
Saccharomyces cerevisiae (1X)	46	15	222.00	4.7×10^3	6,281
E. coli B/r	47	1	335.10	3.0×10^3	6,012
	Radiotaxon V				
Saccharomyces cerevisiae (2X)	48	30	401	1.5×10^4	35,757
Saccharomyces cerevisiae (3X)	49	45	713	1.3×10^4	55,808
Saccharomyces cerevisiae (4X)	50	60	657	1.1×10^4	41,529
Bacillus cereus	51	1	1,796	4.0×10^3	43,679
E. coli B	52	1	3,004	2.4×10^3	43,766
Pseudomonas fluorescens	53	1	9,497	1.1×10^3	60,029
Chick (embryonic wing bud)	54	78	19,396	2.7×10^2	31,293
HeLa clone $S3_{oxf}$	55	70	40,960	1.8×10^2	44,384
Hamster (Chinese) clone V79-1	56	22	40,400	1.4×10^2	32,833
Hamster (Chinese) clone CHL-F	57	46	57,900	1.6×10^2	55,769
Guinea pig (kidney)	58	64	45,660	1.0×10^2	27,487
HeLa clone S3	59	78	72,220	1.4×10^2	60,867
	Radiotaxon VI				
E. coli K12 strain Hfr	60	1	3,527	1.1×10^4	222,925
Chlamydomonas reinhardi	61	16	8,836	2.4×10^3	125,531
Zygnema cruciatum	62	43	15,220	2.1×10^3	196,626
Rana pipiens (liver)	63	26	113,000	1.5×10^2	102,039
Desmognathus fuscus	64	28	202,000	1.4×10^2	164,165
	Radiotaxon VII				
E. coli B_{II}	65	1	8,002	1.2×10^4	616,298
E. coli B_{III}	66	1	8,627	8.1×10^3	421,917
E. coli B_{III} (avg. of #66 and #68)	67	1	17,652	3.8×10^3	398,492
E. coli B_{III} (filamentous form)	68	1	26,677	3.8×10^3	602,229
Oedogonium cardiacum	69	18	64,243	1.3×10^3	514,369
Tradescantia blossfeldiana Mildbr.	70	70	83,000	8.2×10^2	409,721
Marchantia polymorpha L.	71	9	129,000	9.6×10^2	746,348
Tradescantia rosea Vent.	72	24	385,620	3.0×10^2	688,282
T. virginiana L. HV purple dome	73	24	637,000	1.9×10^2	709,465
T. clone 02	74	12	680,200	1.7×10^2	696,117
	Radiotaxon VIII				
Euglena gracilis	75	45	116,000	3.0×10^3	2,094,960
Onoclea sensibilis (24 hr stage)	76	37	258,000	3.3×10^3	5,125,428
Onoclea sensibilis (18 hr stage)	77	37	240,000	2.9×10^3	4,117,680
Onoclea sensibilis (6 hr stage)	78	37	346,000	1.6×10^3	3,228,526
Osmunda regalis (21 hr stage)	79	22	642,590	5.0×10^2	1,934,196

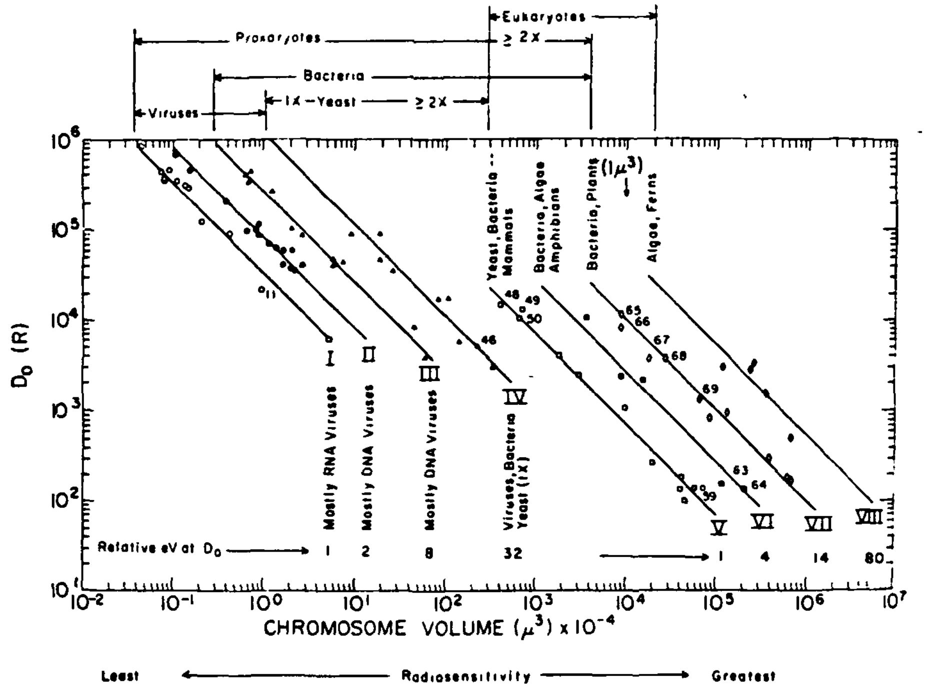

Figure A-13. Correlation Between D_0 and Chromosome Volume

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A.5 RADIATION EFFECTS ON HUMANS

A.5.1 GENERAL

The information concerning human radiation effects that is currently available has been taken from several sources. Atomic bomb victims who are sublethally injured are still being studied as are accident victims, patients given radiation therapy and radiologists who have been exposed to radiation for several years. In addition to these observational studies, considerable animal experiments have been performed which allow extrapolation to humans.

The major effects have been summarized in Table A-23. These effects may be broken into two major groups:

1. Acute or early effects which occur only after relatively high doses (>50 rads) delivered at relatively high dose rates (several rads/hr.). These effects are generally threshold phenomena, are higher dose-rate dependent and the incidence and severity increase nonlinearly with increasing dose.

2. Late or delayed effects are those that appear only after many months or years. They are generally considered to be non-threshold phenomena, are less dose rate dependent than early effects and their occurrence and severity generally appears to be linear and probabilistic functions of the total accumulated dose.

A more detailed description of early and late effects and how these effects are modified is given in the following sections. Dose protraction may be the most important modifying factor with regard to space radiation risk assessment. Solar flares are generally about several rads per hour. These rates may not be high enough to trigger the earliest (prodromol) radiation effects. However, more information on dose rates and environmental factors such as weightlessness is required before definitive predictions of dose-response relationships in manned spacecraft can be accurately made.

Table A-23. Human Radiation Effects

EARLY EFFECTS	CAUSE (RADS)	OBSERVANCE
PRODROMAL	40-400	FEW HOURS
HEMATOLOGICAL AND GERMINAL	100-600	DAYS-WEEKS
SKIN	200->2000	HOURS-WEEKS
GUT	>1000	DAYS-WEEKS
CNS	>6000	IMMEDIATE

DELAYED EFFECTS	CAUSE
LEUKEMIA	$2/10^6$ MAN-YEAR-RAD
LIFE SHORTENING	~6 DAYS/RAD
CATARACTS	150-200 RADS
GENETIC	~100 RADS

EFFECT MODIFICATION

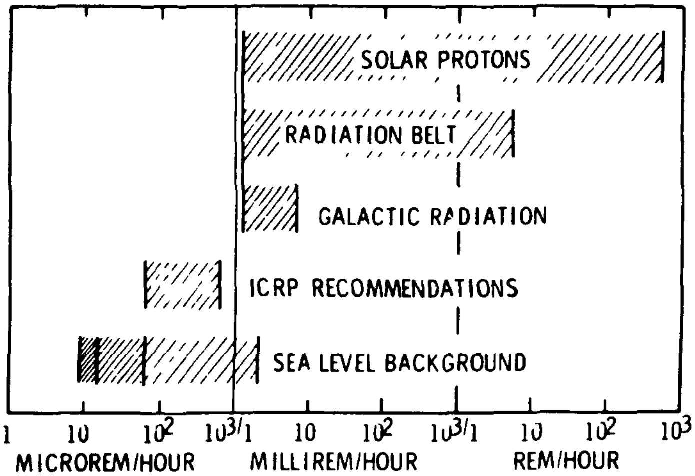
- DOSE
- DOSE RATE
- ENERGY
- RADIATION TYPE
- DOSE PROTRACTION
- DOSE FRACTIONATION
- RECOVERY RATES
- RESIDUAL DAMAGE

A.5.2 RADIATION LEVELS AND LIMITS

Terrestrial radiation levels vary over a rather wide range as shown in Table A-24 (Ref. A.5.1). When these levels are compared with space radiation there is some overlap at the lower levels. Furthermore, the International Commission on Radiation Protection (ICRP) recommended limits for members of the public (lower ICRP limit in Table A-24) and for radiation workers (upper ICRP limit in Table A-24) are exceeded. The upper limit for the general public is 0.5 rem/yr and 5 rem/yr average is generally accepted for radiation workers. Further detail on limits for ground radiation workers is shown in Table A-25 as recommended by the Code of Federal Regulations (Ref. A.5.2) and more recently by the National Committee for Radiation Protection (Ref. A.5.3). Radionuclide limits are given in the supporting data of Section A.5.4.3.

Table A-24. Radiation Level Comparison

LOCATION	RADIATION LEVEL MICROREM/HR	RADIATION LEVEL MILLIREM/YR
MID-ATLANTIC	6	55
NEW YORK CITY	8-15	70-130
STOCKHOLM,		
OUTDOORS	14-17	120-150
HOUSES	17-59	150-520
TRAVANCORE, INDIA	900	8,000
GUARAPARI, BRAZIL,		
HOUSES	103	900
BEACH, AVERAGE	140	1,200
BEACH, HOT SPOT	2,000	17,500



(Ref. A.5 1)

Table A-25. Dose Limits for Ground Radiation Workers

Currently in Use (10 CFR 20) Reference 4-4

Exposure	Condition	Dose (rem)
• WHOLE BODY - Head, trunk, active blood forming organs, gonads, lens of eye	Accumulated Quarterly	5(N-18 yr) 1.25
• SKIN - of whole body	Year Quarterly	30.00 7.50
• HANDS - and forearms, feet and ankles	Year Quarterly	75.00 18.75

Recommended (NCRP-39) Jan. 15, 1971 Reference 4-5

Exposure	Condition	Dose (rem)
• WHOLE BODY	Long Term Accumulated	5(N-18 yr) 5/year
• SKIN	Year	15
• HANDS, FEET & ANKLES	Year Quarterly	75 25
• FOREARMS	Year Quarterly	30 10
• OTHER ORGANS	Year Quarterly	15 5

Table A-26. Crew Radiation Limits (rem) Space Station/Base, Skylab, Shuttle

PRELIMINARY

AREA DEPTH	30 DAY	YEARLY	CAREER
SKIN (0 1 MM)	150	240	2 400
EYE (3 MM)	75	120	1,200
MARROW (5 CM)	25	40	400

NAS SUGGESTED LIMITS

AREA DEPTH	1 YR AVG DAILY	30 DAY	QUARTERLY**	YEARLY	CAREER
SKIN (0 1 MM)	0 6	75	105	225	1 200
EYE (3 MM)	0 3	37	52	112	600
*TESTES (3 CM)	0 1	13	18	38	200
MARROW (5 CM)	0 2	25	35	75	400

*THESE DOSE AND DOSE RATE LIMITS ARE APPLICABLE ONLY WHERE THE POSSIBILITY OF OLIGOSPERMIA AND TEMPORARY INFERTILITY ARE TO BE AVOIDED

**MAY BE ALLOWED FOR TWO CONSECUTIVE QUARTERS FOLLOWED BY SIX MONTHS OF RESTRICTION FROM FURTHER EXPOSURE TO MAINTAIN YEARLY LIMIT

In view of the radiation levels encountered in spacecraft, it became obvious that normal terrestrial limits could not be used unless excessive amounts of shielding were utilized for manned flights. The limits shown in Table A-26 were tentatively released by NASA (Ref. A.5.4, A.5.5, A.5.6, A.5.7), based on information obtained from the Radiobiological Advisory Panel of the National Academy of Sciences (NAS). However, this panel subsequently issued its suggested limits officially in Reference A.5.7. These limits are those shown in Table A-26. They have subsequently been revised to eliminate the testes dose as a primary criterion. If adopted by NASA, these new values will constitute the allowable exposure limits for use in hazards evaluations.

A.5.3 ACCIDENTS

Since accidents such as a reactor failure may occur, consideration must be given to such failures that might exceed the normal limits given above. The accident exposure limits to be used for evaluating the potential hazards to the general populace in case of a nuclear accident are shown in Table A-27. These limits represent what is currently in widespread use in performing terrestrial hazards evaluations associated with reactor site safety, Ref.

A.5.9 and A.5.10. These doses represent once-in-a-lifetime exposure limits. The internal doses are associated with the intake of various radioactive materials (fission products) into the body and considers the fact that the body can retain certain of these radioactive elements for various lengths of time.

Table A-27. Accident Exposure Guidelines General Populace

EXTERNAL EXPOSURE	
• WHOLE BODY	25 REM*
INTERNAL EXPOSURE	
• 70-YEAR BONE DOSE	150 REM**
• THYROID	300 REM*
• LOWER LARGE INTESTINE	75 REM**

*CODE OF FEDERAL REGULATIONS (10 CFR-100)

**DEPT OF MATERIALS AND LICENSING (DML-DOCKET 50-268)

It should also be pointed out that alternate approaches to specifying accident exposure limit criteria for the general populace are currently under study. However, until such criteria became available, the limits specified here will be utilized in subsequent terrestrial hazards analyses. No similar abnormal-situation guidelines have been set for space vehicle crews. Figure A-14, however allows an assessment of mission performance as a function of radiation dose. This figure is a graphical display of some typical early response data which shows the mean time of occurrence for a particular effect as a function of acute whole body exposure. The figure has been constructed such that an estimate of the capability of an individual as a function of time after exposure can be identified for various radiation doses. 50 rads was taken as the limit below which no debilitating effects would occur. Vomiting, on the other hand, was taken as the earliest effect which could incapacitate and individual, at least in particular situations such as EVA. The 10% and 99% vomiting curves are still open to question as a function of modifying factors such as dose protraction, but offer an estimate of the time available for useful performance following acute radiation exposure.

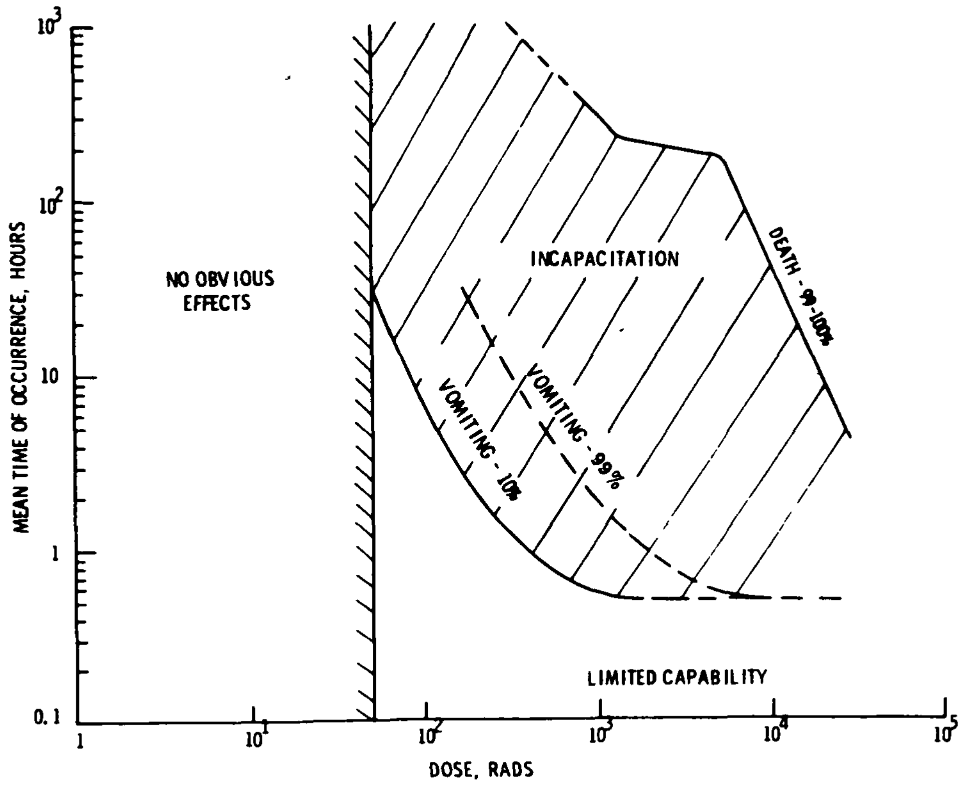


Figure A-14. Early Time Effects - Acute Whole Body Exposure

A.5.4 HUMAN RADIATION EFFECTS CONSIDERATIONS

A.5.4.1 Acute Radiation Effects

Table A-28 gives the expected early effects of acute whole-body radiation. The latency periods and relative duration are dependent upon the penetration, quality factors, total dose, dose distribution and intensity of exposure. Furthermore, it should be noted that this table was generated from terrestrial data. One can only speculate how the dose-response relationship may be altered by weightlessness and the other possible stresses of prolonged space flight. Langham in Reference A.5.12 has suggested that radiation and weightlessness would act additively or synergistically, yet the results (with invertebrates and plants) of the Bios II flight suggest interactions ranging from antagonistic to synergistic.

Table A-28. Expected Early Effects From Acute Whole-Body Radiation on Earth (Modified from Glasstone, 1962) (Ref. A.5.11)

DOSE IN RADS	PROBABLE EFFECT
0-50	No obvious effect, except, possibly, minor blood changes and anorexia.
50-100	Vomiting and nausea for about 1 day in 10 to 20% of exposed personnel. Fatigue, but no serious disability. Transient reduction in lymphocytes and neutrophils.
100-200	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in up to 50% of personnel; 5% deaths anticipated. A reduction of approximately 50% in lymphocytes and neutrophils will occur.
200-350	Vomiting and nausea in 50 to 90% of personnel on first day, followed by other symptoms of radiation sickness, e.g., loss of appetite, diarrhea, minor hemorrhage; 5 to 90% deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
350-550	Vomiting and nausea in most personnel on first day, followed by other symptoms of radiation sickness, e.g., fever, hemorrhage, diarrhea, emaciation. Over 90% deaths within 1 month; survivors convalescent for about 6 months.
550-750	Vomiting and nausea, or at least nausea, in all personnel within four hours from exposure, followed by severe symptoms of radiation sickness, as above. Up to 100% deaths; few survivors convalescent for about six months.
1,000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5,000	Incapacitation almost immediately (several hours). All personnel will be fatalities within one week.

Prodromal Sequelae - The earliest signs and symptoms of high-intensity radiation exposure are those of the prodromal reaction (anorexia, nausea and vomiting). These signs and symptoms may begin to appear in less than 1-2 hours of exposure and may subside in less than 1-2 days. Estimated absorbed doses to produce these sequelae for a 26 cm sphere in the mid-epigastic region is given in Table A-29.

Table A-29. Estimated High-Intensity Radiation Dose Levels for Production of Early Prodromal Response

(After Langham, ed., NAS-NRC, 1967) (Ref. A.5.12)

CLINICAL SIGNS	ABSORBED DOSE FOR PROBABILITY OF RESPONSE (RADS)		
	10%	50%	90%
Anorexia	40	100	240
Nausea	50	170	320
Vomiting	60	215	380
Diarrhea	90	240	390

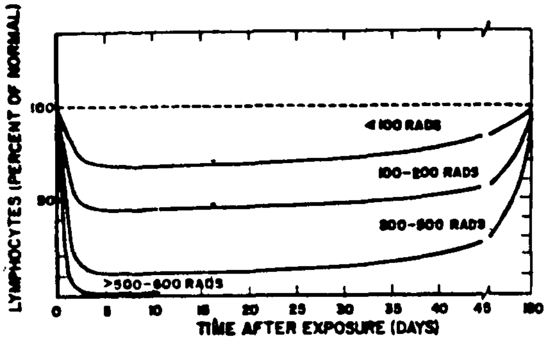
Hematological Effects - Hematological responses to radiation are largely dependent on damage to the marrow and lymphoid tissue. Inhibition of cell division results in decreased blood counts as seen in Figure A-15. The time course of changes in most of the peripheral-blood elements is fairly well correlated with the dose of radiation of the bone marrow:

1. Survival almost certain - < 100 rads
2. Survival probable - 100-200 rads
3. Survival possible - 200-500 rads
4. Survival very improbable > 500-600 rads

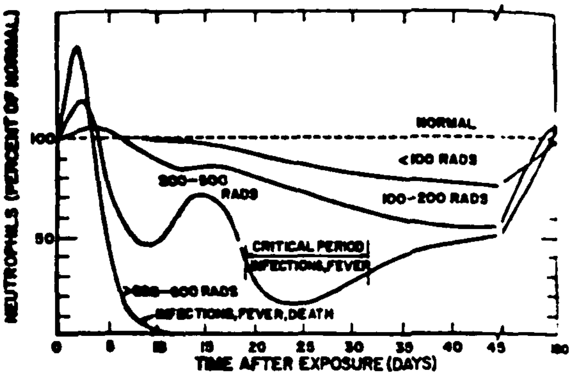
The principal locations of active bone marrow are the pelvis, spine, ribs and proximal ends of the bones of the extremities. The depth of the marrow varies from 1 to 15 cm. For calculation of assessment of dose to the blood forming tissues, the average effective depth is given as 5 cm. Figure A-16 shows the relationship between dose survival in man and points out that the hematopoietic system is the most sensitive to radiation, followed by the gastro-intestinal tract and the central nervous system.

Skin and Germinal Epithelium Reactions - A summary of skin radiation damage is given in Table A-30. The doses required to produce effects are decidely in the lethal range, but penetration need only be very slight (usually given for a 0.1 mm depth). It is possible to

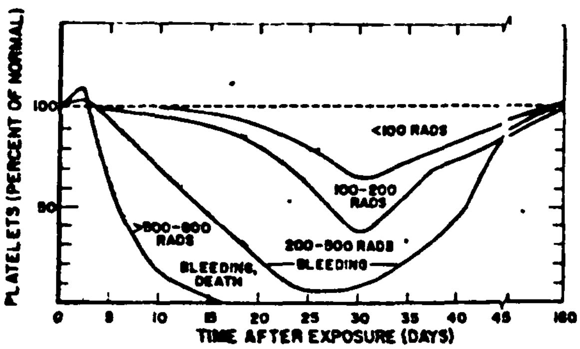
(After Langham, ed., NAS-NRC, 1967) (Ref. A.5.12)



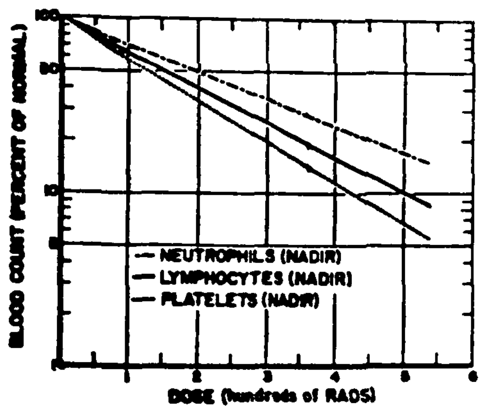
a. Smoothed Average Time-Course of Lymphocyte Changes in Human Cases from Accidental Radiation Exposure as a Function of Dose.



b. Smoothed Average Time-Course of Neutrophil Changes in Human Cases from Accidental Radiation Exposure as a Function of Dose.



c. Smoothed Average Time-Course of Platelet Changes in Human Cases from Accidental Radiation Exposure as a Function of Dose.



d. Idealized Average Dose-Response Relationship for Lymphocytes, Neutrophils, and Platelets in which the Nadir of Each Blood Element is Plotted Against Dose.

Figure A-15. The Time Course of Blood Changes After Different Doses of Radiation of QF = 1

Table A-30. Radiation Damage to the Skin*
(After Grahn, 1964) (Ref. A.5.13)

EPILATION LOSS OF HAIR	ERYTHEMA (FIRST DEGREE BURNS)	MOIST DESQUAMATION AND BLISTERING (SECOND DEGREE BURNS)	ULCERATION (THIRD DEGREE BURNS)
Rare at less than 200 r			
Partial epilation at 350-450 r	Response is dependent on energy, dose rate, area exposed, and complexion of the individual. Full effect in 1 to 3 weeks after:		
Complete epilation in 16-18 days at $>$450 r	200-400 r ($<$150 kev) 500-600 r (200-400 kev) 800-1000 r ($>$400 kev)		
Permanent epilation at $>$ 700 r	Response in first hours at 1000 r	Effect in 1-2 weeks at $>$1000 r	
			Rapidly progressive effect at $>$2000 r

*These statements are based on air doses. Dose estimates are at 0.1 mm depth where 1 r $\cong$ 1 rad.

have a very high skin dose and a very low marrow dose (5 cm) if the radiation has a low penetration, as may be the case with alpha particles.

This curve is extrapolated from animal studies and very few human studies. It holds only for acute total body radiation. Note spread of data.

(After Grahn, 1964) (Ref. A.5.13)

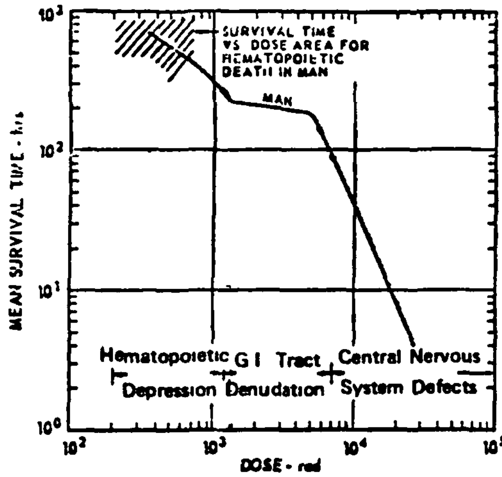


Figure A-16. The Relationship Between Mean Survival Time and Acute Radiation Dose for Man

The rapid division rate of the gametogenic epithelium makes this tissue quite sensitive to radiation. Damage to male gonads is given in Table A-31.

A.5.4.2 <u>Delayed Radiation Effects</u>

<u>Ocular Lens</u> - About 150-200 rads is the minimal cataractogenic single-exposure dose. Six hundred and fifty to seven hundred and fifty (650-750) rads may give a cataractogenic probability approaching unity. The time of appearance of cataracts is highly variable and may range from as early as six months to several years after exposure.

<u>Skin Effects</u> - Depending on total dose and protraction, late radiation changes in skin vary from minor telangiectasia of cosmetic interest only to development of the most serious sequela, metastatic carcinoma. However, quantitative dose-response relationships for the various manifestations of chronic radio-dermatitis do not exist. There seems to be a correlation, however, between production of an early desquamation reaction and manifestations of minimal late effects (telangiectasias, mottled pigmentation) in that clinically-evident permanent changes are observed regularly after early desquamation. Based on this premise, the single-exposure dose-response relationship for production of minimal late changes in the skin would be parallel to and approximately the same as that for early moist desquamation. Back extrapolation from protracted dose schedules suggest a single-dose equivalent of ~ 2,800 rads (small exposure fields ~ 10 cm^2) for production of 50 percent probability of late necrosis.

Table A-31. Radiation Damage to Gonads

DOSE	RESPONSE
15-100 rad	Progressive reduction in fertility with dose reduced sperm count (oligospermia) and increased frequency of abnormal sperm. Above 100 rads, azoospermia is usually evident at 10 weeks.
200-300 rad	Temporary, absolute sterility (azoospermia) for approximately 12-15 months after 10 weeks.
400-500 rad	Temporary sterility for 18-24 months.
500-600 rad	Probably permanent sterility, if individual survives.

Life Shortening - In view of the lack of human data on the effect of radiation on life shortening, estimates must be made from animal studies plus some data available on the mortality rates of American radiobiologists. These data are summarized along with leukemia incidence (which contributes to life shortening) in Tables A-32 and A-33 and Figures A-17 and A-18.

Table A-32. Suggested Reference Radiation Dose-Response Relationships for General Life-Shortening and Increased Incidence of Leukemia

(After Langham, ed., NAS-NRC, 1967) (Ref. A.5.12)

RESPONSE	HIGH INTENSITY EXPOSURE*	LOW INTENSITY EXPOSURE**
Life Shortening***	~ 10 days/rad	~ 3 days/rad
Leukemia***	2-4 per 10^6 man-yr/rad	1-2 per 10^6 man-yr/rad

*Assumed to be 50 rads/day and greater

**Assumed to be 1 rad/day and less

***Site of interest for dose estimation, 5 cm depth; whole-body exposure

Table A-33. Estimates for Life-Shortening of Man From Exposure to High-Let Ionizing Radiation

(After Schaefer, 1966) (Ref. A.5.17)

TYPE OF RADIATION	LIFE SHORTENING, DAYS/RAD	
	ACUTE EXPOSURE	CHRONIC EXPOSURE
Low LET (Electrons, x- or gamma rays)	12	3
High LET (Low-E protons or neutrons, medium and high-E heavy nuclei)	24	24
Extremely high LET ("Microbeams" of heavy nuclei enders)	?	?

Genetic Manifestations - The National Research Council Committee on Genetic Effects of Atomic Radiation recommends that the dose be kept below 10 rads/generation, or about 0.3 rads/year (Ref. A.5.18, A.5.12). The International Commission on Radiological Protection recommends about 0.17 rads/year (Ref. A.5.19). An astronaut undoubtedly receives gonad doses greater than these. The probability of a new mutation in immediate offspring (based on animal data) is considerably less than 1% for a dose of 100 rads. Thus, the genetic risk is rather low. Since the mutation rate in the advanced germinal cell stages of the mouse is 2-3 times that observed in the spermatogonia, it can be recommended that conception of offspring be avoided

(After Langham, ed., NAS-NRC, 1967) (Ref. A.5.12)

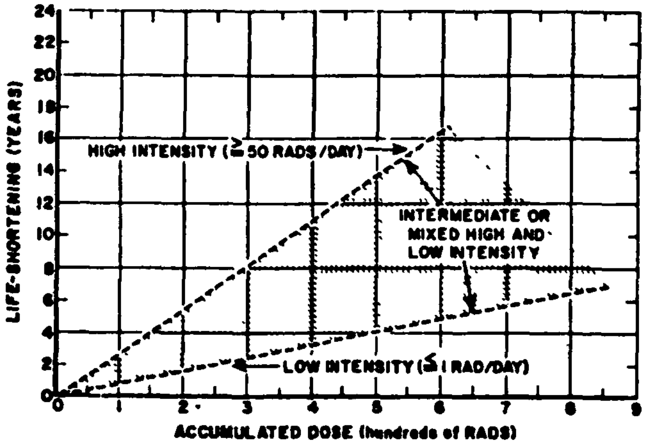


Figure A-17. Relationship of Accumulated Dose and Intensity of Reference-Quality Whole-Body Radiation to Life-Shortening Probability

during the post flight stages in which irradiated postgonial cell stages are still present (Ref. A.5.20).

A.5.4.3 Radiation Quality Type

The unit of absorbed dose is the rad, which is equal to an energy deposition of 100 ergs/g. (One roentgen is equivalent to 93 ergs/g of soft tissue). The absorbed dose is imparted by ionization per unit mass of irradiated material. The average ionization energy in tissue = 5.82 x 10^{-11} erg/ion pair or 1.72 x 10^{12} ion pairs/g of tissue-rad. The energy expended in producing one ion pair in tissue is about 35 eV. Since radiations of different type and quality (mass, charge, energy) produce different spatial distributions of energy deposition in tissue, different biological responses per unit of absorbed dose are to be expected. Two terms are currently used to account for these differences. The older term is relative biological effectiveness (RBE); which is defined as the ratio of the dose (in rads) of high energy X or gamma rays required to produce a specific level of biological effect to the dose (in rads) of another radiation required to produce the same level of effect. RBE is mainly a function of the ionization energy per micron of tissue - linear energy transfer (LET). However, the state of the tissue (metabolic rate, oxygenation, etc.) can modify the tissue response. In order to allow radiation protection calculations based on LET, the term quality factor (QF) has been introduced. The product of the absorbed dose (in rads) and QF gives the dose equivalent (DE) in rems. The National Committee on Radiation Protection (Ref. A.5.21) has proposed the QF-LET relationship shown in Table A-34. The QF values given refer to late or delayed effects of low dose-rate exposure. These effects are usually more dependent on LET than large doses delivered at high dose rates. To a first approximation, the relationship for

(After Langham, ed., NAS-NRC, 1967)
(Ref. A.5.12)

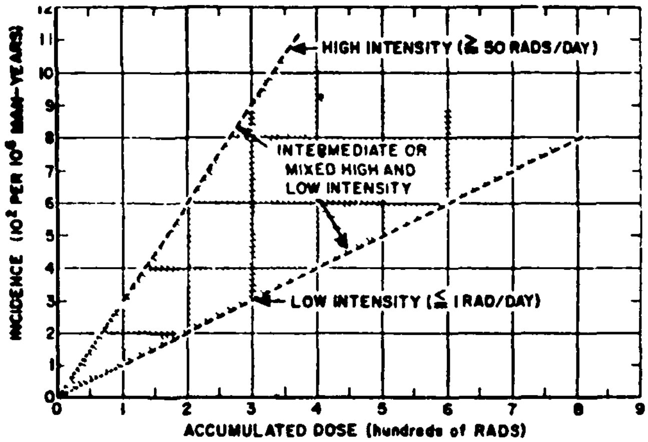


Figure A-18. Relationship of Accumulated Dose and Intensity of Reference Quality Whole-Body Radiation to Increased Probability to Leukemia

delayed effects of low dose-rate exposure is: $QF = 0.8 + 0.16\ L$, where L is the mean LET in KeV/μ (Ref. A.5.22). For large doses at high dose rate $QF = 0.9 + 0.05\ L$. The QF values given in Table A-35 have been suggested by NAS-NRC for space radiation. Table A-36 gives QF values for several types of radiation for low dose rates. Although QF values of around 10 for late effects are assigned to protons of 0.5 MeV and less, Schaefer (Ref. A.5.23, 24, 25, 26, 27) has shown that the mean local QF values for space protons and alpha particles behind moderate shielding can never greatly exceed unity because of the small fraction of the total dose delivered at high LET. For solar flare protons with light prefiltration (2 g/cm^2), a maximum QF of 1.46 for late effects occurs at the surface of the target and approaches unity as a function of depth. QF values of fission neutrons (0.5 - 1 MeV) for production of early response range from ~ 1 to ~ 3 based on animal studies.

Table A-34. Values of QF_L for Late or Delayed Effects as a Function of Average LET (Ref. A.5.21)

LET (KeV/µ In Water)	QF
X Rays and Electrons in any LET	1
3.5 or less	1
3.5 - 7	1 - 2
7 - 23	2 - 5
23 - 53	5 - 10
53 - 175	10 - 20

Internally Deposited Radiosiotopes

Internal radiation poses a somewhat different problem than external radiation as discussed above. Two different criteria are used depending on the type of isotope under consideration. For bone-seeking radioisotopes such as ^{90}Sr, ^{227}Ac, ^{232}Th, ^{231}Pa, ^{237}Np, ^{239}Pu, etc., which emit alpha or beta radiation, the maximum permissible body burden is based on a comparison with ^{226}Ra and its daughters. 0.1 μg of radium in equilibrium with its decay products gives a dose equivalent to the bone of 0.56 rem/week. A QF of 10 is assumed in computing this DE - other bone seekers may have a lower QF which is attributed to the greater degree of non-uniformity of deposition of the other bone seekers. For this reason, another factor, called the relative damage factor (DF) is used as a multiplier of QF. This factor has a value of 5 for alpha or beta radiation, except where the corpuscular radiations

Table A-35. Suggested QF_E Values for Early Effects of High-Intensity Space-Radiation Exposure

(After Langham, ed., NAS-NRC, 1967) (Ref. A.5.12)

	COMPONENT	QF
Skin Responses	Low Let (≦ 3.5 KeV/μ)	1
	High Let (> 3.5 KeV/μ)	3
Prodromal Syndrome	Total Flux	1
Hematological Responses	Total Flux	1
Lethality, Hematological Syndrome	Total Flux	1
Lethality, Intestinal Syndrome	Low Let (≦ 3.5 KeV/μ)	1
	High Let (> 3.5 KeV/μ)	3
Atrophy of germinal Epithelium	Low Let (≦ 3.5 KeV/μ)	1
	High Let (> 3.5 KeV/μ)	3

Table A-36. Typical QF_L for Late Effects at Low Dose Rate in Ground-Based Exposure

TYPE OF RADIATION	RBE or QF
X-rays	1
Gamma Rays	1
Beta Particles, 1.0 mev	1
Beta Particles, 0.1 mev	1
Neutrons, Thermal Energy	2.8
Neutrons, 0.0001 mev	2 2
Neutrons, 0.005 mev	2.4
Neutrons, 0.02 mev	5
Neutrons, 0.5 mev	10.2
Neutrons, 1.0 mev	10.5
Neutrons, 10.0 mev	6 4
Protons, greater than 100 mev	1 - 2
Protons, 1 0 mev	8 5
Protons, 0.1 mev	10
Alpha Particles, 5 mev	15
Alpha Particles, 1 mev	20

are due to a decay chain whose first member is radium. When radium is the first member of the chain, DF = 1. The energy dissipated in the bone by ^{226}Ra and the daughters that remain in the bone is MeV/disintegration or 110 MeV with a QF of 10. Since 99% of the ^{226}Ra body burden is in the skeleton, the burden for any other bone seeker equivalent to 0.56 rem/ week is:

$$q = \frac{0.1\,\mu\,\text{Ci} \times 0.99}{f_2} \quad x \quad \frac{110\ \text{MeV/d}}{\text{E MeV/d}} = \frac{11}{f_2 E}$$

where E is the effective corpuscular energy per disintegration of any other bone seeker and f_2 is the fraction of the total body burden of bone seeker in the skeleton. In the case of ^{90}Sr - ^{90}Y, where the average energy = 1.12 MeV/hour , QF = 1 and DF = 5, q = 2 μ Ci. However, since the effective half life of ^{90}Sr is 18 years, 50 years will be required for an 86% equilibrium (Ref. A.5.28). For non bone-seekers, the matter is similar to external radiation. If the permissible body burden and information regarding metabolism are known, the concentration in air and water that would produce a certain dose may be calculated. Table A-37 gives radioisotope burdens based on 100 mrem/week to the total body, gonads or hematopoietic system or 300 mrem/week to other organs.

A.5.4.4 Chemical and Biological Protection

1. Pre-irradiation Treatment with Chemical Agents (Prophylaxis)

   Several reviews of chemical protection are available (Straube and Patt, 1963; Schubert, 1964, Bacq. 1965). Unfortunately, no work has been done on humans - most of the testing has been done on mice, with only a few studies with larger animals. A large number of compounds probably protect by reducing the oxygen pressure in tissues. Morphine, ethanol, carbon monoxide, p-aminopropriophenone (PAPP), epinephrine, sodium nitrate, histamine, methacholene and 5-hychoxytryptamine (serotonin) are examples of materials that protect mainly via hypoxia. Of these compounds, PAPP and serotonin appear superior, giving a dose-reduction factor of about 1.5 to 1.6. Where the dose reduction factor is defined as:

$$\frac{LD_{50-30}\ \text{(protected)}}{LD_{50-30}\ \text{(control)}}$$

Table A-37. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure

(After Cember, 1969) (Ref. A.5.28)

Radionuclide and type of decay		Organ of reference[a] (critical organ in bold type)	Maximum permissible burden in total body $q(\mu c)$	Maximum permissible concentrations			
				For 40-hr week		For 168-hr week[b]	
				$(MPC)_w$ $\mu Ci/cm^3$	$(MPC)_a$ $\mu Ci/cm^3$	$(MPC)_w$ $\mu Ci/cm^3$	$(MPC)_a$ $\mu Ci/cm^3$
$^3_1H_2(H^3O)$ (β^-)	(Sol)	**Body tissue**	10^3	0 1	2×10^{-5}	0 03	5×10^{-6}
		Total body	2×10^3	0 2	2×10^{-5}	0 05	7×10^{-6}
(H^3_2)	(Immersion)	**Skin**			2×10^{-3}		4×10^{-4}
$^{14}_6C(CO_2)$ (β^-)	(Sol)	**Fat**	300	0 02	4×10^{-6}	8×10^{-3}	10^{-6}
		Total body	400	0 03	5×10^{-6}	0 01	2×10^{-6}
		Bone	400	0 04	6×10^{-6}	0 01	2×10^{-6}
	(Immersion)	**Total body**			5×10^{-5}		10^{-3}
$^{32}_{15}P$ (β^-)	(Sol)	**Bone**	6	5×10^{-4}	7×10^{-8}	2×10^{-4}	2×10^{-8}
		Total body	30	3×10^{-3}	4×10^{-7}	9×10^{-4}	10^{-7}
		GI (LLI)		3×10^{-3}	6×10^{-7}	9×10^{-4}	2×10^{-7}
		Liver	50	5×10^{-3}	6×10^{-7}	2×10^{-3}	2×10^{-7}
		Brain	300	0 02	3×10^{-6}	8×10^{-3}	10^{-6}
	(Insol)	**Lung**			8×10^{-8}		3×10^{-8}
		GI (LLI)		7×10^{-4}	10^{-7}	2×10^{-4}	4×10^{-8}
$^{45}_{20}Ca$ (β^-)	(Sol)	**Bone**	30	3×10^{-4}	3×10^{-8}	9×10^{-5}	10^{-8}
		Total body	200	2×10^{-3}	3×10^{-7}	7×10^{-4}	9×10^{-5}
		GI (LLI)		0 01	3×10^{-8}	4×10^{-3}	10^{-8}
	(Insol)	**Lung**			10^{-7}		4×10^{-8}
		GI (LLI)		5×10^{-3}	9×10^{-7}	2×10^{-3}	3×10^{-7}
$^{51}_{24}Cr$ (ec, γ)	(Sol)	**GI (LLI)**		0 05	10^{-5}	0 02	4×10^{-6}
		Total body	800	0 6	10^{-5}	0 2	4×10^{-6}
		Lung	10^3	1	2×10^{-6}	0 4	8×10^{-6}
		Prostate	2×10^3	2	3×10^{-5}	0 5	10^{-5}
		Thyroid	4×10^3	3	6×10^{-5}	1	2×10^{-5}
		Kidney	8×10^3	6	10^{-4}	2	4×10^{-5}
	(Insol)	Lung			2×10^{-6}		8×10^{-8}
		GI (LLI)		0 05	8×10^{-6}	0 02	3×10^{-6}
$^{60}_{27}Co$ (β^-, γ)	(Sol)	**GI (LLI)**		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
		Total body	10	4×10^{-3}	4×10^{-7}	10^{-3}	10^{-7}
		Pancreas	70	0 02	2×10^{-6}	7×10^{-3}	6×10^{-7}
		Liver	90	0 03	10^{-6}	9×10^{-3}	5×10^{-7}
		Spleen	200	0 05	4×10^{-6}	0 02	2×10^{-6}
		Kidney	200	0 07	6×10^{-6}	0 03	2×10^{-6}
	(Insol)	**Lung**			9×10^{-9}		3×10^{-9}
		GI (LLI)		10^{-3}	2×10^{-7}	3×10^{-4}	6×10^{-9}

Table A-37. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure (Cont'd)

Radionuclide and type of decay		Organ of reference[a] (critical organ in bold type)	Maximum permissible burden in total body $q(\mu c)$	Maximum permissible concentrations: For 40-hr week $(MPC)_w$ $\mu Ci/cm^3$	For 40-hr week $(MPC)_a$ $\mu Ci/cm^3$	For 168-hr week[b] $(MPC)_w$ $\mu Ci/cm^3$	For 168-hr week[b] $(MPC)_a$ $\mu Ci/cm^3$
$^{65}_{30}$Zn (β^+, ϵ, γ)	(Sol)	**Total body**	60	3×10^{-3}	10^{-7}	10^{-3}	4×10^{-8}
		Prostate	70	4×10^{-3}	10^{-7}	10^{-3}	4×10^{-8}
		Liver	80	4×10^{-3}	10^{-7}	10^{-3}	5×10^{-8}
		Kidney	100	6×10^{-3}	2×10^{-7}	2×10^{-3}	7×10^{-8}
		GI (LLI)		6×10^{-3}	10^{-6}	2×10^{-3}	4×10^{-7}
		Pancreas	200	7×10^{-3}	3×10^{-7}	3×10^{-3}	9×10^{-8}
		Muscle	200	0.01	4×10^{-7}	4×10^{-3}	10^{-7}
		Ovary	300	0.01	5×10^{-7}	4×10^{-3}	2×10^{-7}
		Testis	400	0.02	6×10^{-7}	6×10^{-3}	2×10^{-7}
		Bone	700	0.04	10^{-6}	0.01	4×10^{-7}
	(Insol)	**Lung**			6×10^{-8}		2×10^{-8}
		GI (LLI)		5×10^{-3}	9×10^{-7}	2×10^{-3}	3×10^{-7}
$^{76}_{33}$As (β^-, γ)	(Sol)	**GI (LLI)**		6×10^{-4}	10^{-7}	2×10^{-4}	4×10^{-8}
		Total body	20	0.4	5×10^{-6}	0.1	2×10^{-6}
		Kidney	20	0.6	8×10^{-6}	0.2	3×10^{-6}
		Liver	40	1	10^{-5}	0.4	5×10^{-6}
	(Insol)	**GI (LLI)**		6×10^{-4}	10^{-7}	2×10^{-4}	3×10^{-8}
		Lung			6×10^{-7}		2×10^{-7}
$^{89}_{38}$Sr (β^-)	(Sol)	**Bone**	4	3×10^{-4}	3×10^{-8}	10^{-4}	10^{-8}
		GI (LLI)		10^{-3}	3×10^{-7}	4×10^{-4}	9×10^{-8}
		Total body	40	2×10^{-3}	2×10^{-7}	7×10^{-4}	6×10^{-8}
	(Insol)	**Lung**			4×10^{-8}		10^{-8}
		GI (LLI)		8×10^{-4}	10^{-7}	3×10^{-4}	5×10^{-8}
$^{90}_{38}$Sr (β^-)	(Sol)	**Bone**	2	4×10^{-6}	3×10^{-10}	10^{-6}	10^{-10}
		Total body	20	10^{-5}	9×10^{-10}	4×10^{-6}	3×10^{-10}
		GI (LLI)		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
	(Insol)	**Lung**			5×10^{-9}		2×10^{-9}
		GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	6×10^{-8}
$^{95}_{40}$Zr (β^-, γ, e^-).	(Sol)	**GI (LLI)**		2×10^{-3}	4×10^{-7}	6×10^{-4}	10^{-7}
		Total body	20	3	10^{-8}	1	4×10^{-9}
		Bone	30	4	2×10^{-7}	2	6×10^{-8}
		Kidney	30	4	2×10^{-7}	2	6×10^{-8}
		Liver	40	6	3×10^{-7}	2	9×10^{-8}
		Spleen	40	7	3×10^{-7}	2	10^{-7}
	(Insol)	**Lung**			3×10^{-8}		10^{-8}
		GI (LLI)		2×10^{-3}	3×10^{-7}	6×10^{-4}	10^{-7}
$^{95}_{41}$Nb (β^-, γ)	(Sol)	**GI (LLI)**		3×10^{-3}	6×10^{-7}	10^{-3}	2×10^{-7}
		Total body	40	10	5×10^{-7}	4	2×10^{-7}
		Liver	60	20	7×10^{-7}	6	3×10^{-7}
		Kidney	60	20	8×10^{-7}	6	3×10^{-7}
		Bone	80	20	9×10^{-7}	7	3×10^{-7}
		Spleen	80	20	10^{-6}	7	3×10^{-7}

Table A-37. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure (Cont'd)

Radionuclide and type of decay		Organ of reference[a] (critical organ in bold type)	Maximum permissible burden in total body $q(\mu c)$	Maximum permissible concentrations: For 40-hr week $(MPC)_w$ $\mu Ci/cm^3$	For 40-hr week $(MPC)_a$ $\mu Ci/cm^3$	For 168-hr week[b] $(MPC)_w$ $\mu Ci/cm^3$	For 168-hr week[b] $(MPC)_a$ $\mu Ci/cm^3$
	(Insol)	**Lung**			10^{-7}		3×10^{-8}
		GI (LLI)		3×10^{-3}	5×10^{-7}	10^{-3}	2×10^{-7}
$^{106}_{44}$Ru (β^-, γ)	(Sol)	**GI (LLI)**		4×10^{-4}	8×10^{-8}	10^{-4}	3×10^{-8}
		Kidney	3	0.01	10^{-7}	4×10^{-3}	5×10^{-8}
		Bone	10	0.04	5×10^{-7}	0.01	2×10^{-7}
		Total body	10	0.06	7×10^{-7}	0.02	3×10^{-7}
	(Insol)	**Lung**			6×10^{-9}		2×10^{-9}
		GI (LLI)		3×10^{-4}	6×10^{-8}	10^{-4}	2×10^{-8}
$^{131}_{53}$I (β^-, γ, e^-)	(Sol)	**Thyroid**	0.7	6×10^{-5}	9×10^{-9}	2×10^{-5}	3×10^{-9}
		Total body	50	5×10^{-3}	8×10^{-7}	2×10^{-3}	3×10^{-7}
		GI (LLI)		0.03	7×10^{-6}	0.01	2×10^{-6}
	(Insol)	**GI (LLI)**		2×10^{-3}	3×10^{-7}	6×10^{-4}	10^{-7}
		Lung			3×10^{-7}		10^{-7}
$^{137}_{55}$Cs (β, γ, e^-)	(Sol)	**Total body**	30	4×10^{-4}	6×10^{-8}	2×10^{-4}	2×10^{-8}
		Liver	40	5×10^{-4}	8×10^{-8}	2×10^{-4}	3×10^{-8}
		Spleen	50	6×10^{-4}	9×10^{-8}	2×10^{-4}	3×10^{-8}
		Muscle	50	7×10^{-4}	10^{-7}	2×10^{-4}	4×10^{-8}
		Bone	100	10^{-3}	2×10^{-7}	5×10^{-4}	7×10^{-8}
		Kidney	100	10^{-3}	2×10^{-7}	5×10^{-4}	8×10^{-8}
		Lung	300	5×10^{-3}	6×10^{-7}	2×10^{-3}	2×10^{-7}
		GI (SI)		0.02	5×10^{-6}	8×10^{-3}	2×10^{-6}
	(Insol)	**Lung**			10^{-8}		5×10^{-9}
		GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	8×10^{-8}
$^{144}_{58}$Ce (α, β^-, γ)	(Sol)	**GI (LLI)**		3×10^{-4}	8×10^{-8}	10^{-4}	3×10^{-8}
		Bone	5	0.2	10^{-8}	0.08	3×10^{-9}
		Liver	6	0.3	10^{-8}	0.1	4×10^{-9}
		Kidney	10	0.5	2×10^{-8}	0.2	7×10^{-9}
		Total body	20	0.7	3×10^{-8}	0.3	10^{-8}
	(Insol)	**Lung**			6×10^{-9}		2×10^{-9}
		GI (LLI)		3×10^{-4}	6×10^{-8}	10^{-4}	2×10^{-8}
$^{147}_{61}$Pm (α, β^-)	(Sol)	**GI (LLI)**		6×10^{-3}	10^{-6}	2×10^{-3}	5×10^{-7}
		Bone	60	1	6×10^{-8}	0.5	2×10^{-8}
		Kidney	200	4	2×10^{-7}	2	7×10^{-8}
		Total body	300	7	3×10^{-7}	2	10^{-7}
		Liver	300	8	4×10^{-7}	3	10^{-7}
	(Insol)	**Lung**			10^{-7}		3×10^{-8}
		GI (LLI)		6×10^{-3}	10^{-6}	2×10^{-3}	4×10^{-7}
$^{182}_{73}$Ta (β^-, γ)	(Sol)	**GI (LLI)**		10^{-3}	3×10^{-7}	4×10^{-4}	9×10^{-8}
		Liver	7	0.9	4×10^{-8}	0.3	10^{-8}
		Kidney	20	2	8×10^{-8}	0.7	3×10^{-8}
		Total body	20	2	9×10^{-8}	0.7	3×10^{-8}
		Spleen	30	4	10^{-7}	1	5×10^{-8}
		Bone	50	6	3×10^{-7}	2	9×10^{-8}

Table A-37. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure (Cont'd)

Radionuclide and type of decay		Organ of reference[a] (critical organ in bold type)	Maximum permissible burden in total body $q(\mu c)$	Maximum permissible concentrations			
				For 40-hr week		For 168-hr week[b]	
				$(MPC)_w$ $\mu Ci/cm^3$	$(MPC)_a$ $\mu Ci/cm^3$	$(MPC)_w$ $\mu Ci/cm^3$	$(MPC)_a$ $\mu Ci/cm^3$
	(Insol)	**Lung**			2×10^{-8}		7×10^{-9}
		GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	7×10^{-8}
$^{192}_{77}Ir$ (β^-, γ)	(Sol)	**GI (LLI)**		10^{-3}	3×10^{-7}	4×10^{-4}	9×10^{-8}
		Kidney	6	4×10^{-3}	10^{-7}	10^{-3}	4×10^{-8}
		Spleen	7	4×10^{-3}	10^{-7}	10^{-3}	5×10^{-8}
		Liver	8	5×10^{-3}	2×10^{-7}	2×10^{-3}	6×10^{-8}
		Total body	20	0.01	4×10^{-7}	4×10^{-3}	10^{-7}
	(Insol)	**Lung**			3×10^{-8}		9×10^{-9}
		GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	6×10^{-8}
$^{198}_{79}Au$ (β^-, γ)	(Sol)	**GI (LLI)**		2×10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
		Kidney	20	0.07	3×10^{-6}	0.02	9×10^{-7}
		Total body	30	0.1	4×10^{-6}	0.04	2×10^{-6}
		Spleen	60	0.2	8×10^{-6}	0.07	3×10^{-6}
		Liver	80	0.3	10^{-5}	0.1	4×10^{-6}
	(Insol)	**GI (LLI)**		10^{-3}	2×10^{-7}	5×10^{-4}	8×10^{-8}
		Lung			6×10^{-7}		2×10^{-7}
$^{222}_{86}Rn$[c] (α, β, γ)		**Lung**			3×10^{-8}		10^{-8}
$^{226}_{88}Ra$ $(\alpha, \beta^-, \gamma)$	(Sol)	**Bone**	0.1	4×10^{-7}	3×10^{-11}	10^{-7}	10^{-11}
		Total body	0.2	6×10^{-7}	5×10^{-11}	2×10^{-7}	2×10^{-11}
		GI (LLI)		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
	(Insol)	GI (LLI)		9×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
$^{233}_{92}U$ $(\alpha, \beta^-, \gamma)$	(Sol)	GI (LLI)		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
		Kidney	0.03	0.01	5×10^{-10}	4×10^{-3}	2×10^{-10}
		Bone	0.06	0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
		Total body	0.4	0.04	2×10^{-9}	0.01	6×10^{-10}
	(Insol)	Lung			10^{-10}		4×10^{-11}
		GI (LLI)		8×10^{-4}	10^{-7}	3×10^{-4}	5×10^{-8}
$^{235}_{92}U$ (α, γ, e^-)	(Sol)	GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	8×10^{-8}
		Kidney	5×10^{-3}	2×10^{-3}	7×10^{-11}	6×10^{-4}	3×10^{-11}
		Bone	0.06	0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
		Total body	0.5	0.04	2×10^{-9}	0.01	6×10^{-10}
	(Insol)	Lung			10^{-10}		5×10^{-11}
		GI (LLI)		10^{-3}	2×10^{-7}	4×10^{-4}	6×10^{-8}
$^{239}_{94}Pu$ (α, γ)	(Sol)	Bone	0.04	10^{-4}	2×10^{-12}	5×10^{-5}	6×10^{-13}
		Liver	0.4	5×10^{-4}	7×10^{-12}	2×10^{-4}	2×10^{-12}
		Kidney	0.5	7×10^{-4}	9×10^{-12}	2×10^{-4}	3×10^{-12}
		GI (LLI)		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
		Total body	0.4	10^{-3}	10^{-11}	3×10^{-4}	5×10^{-12}
	(Insol)	Lung			4×10^{-11}		10^{-11}
		GI (LLI)		8×10^{-4}	2×10^{-7}	3×10^{-4}	5×10^{-8}

[a] The abbreviations GI, S, SI, ULI, and LLI refer to gastrointestinal tract, stomach, small intestines, upper large intestine, and lower large intestine, respectively.

[b] It will be noted that the MPC values for the 168-hr week are not always precisely the same multiples of the MPC for the 40-hr week. Part of this is caused by rounding off the calculated values to one digit, but in some instances it is due to technical differences discussed in the ICRP report. Because of the uncertainties present in much of the biological data and because of individual variations, the differences are not considered significant The MPC values for the 40-hr week are to be considered as basic for occupational exposure, and the value for the 168-hr week are basic for continuous exposure as in the case of the population at large

[c] The daughter isotopes of ^{220}Rn and ^{222}Rn are assumed present to the extent they occur in unfiltered air For all other isotopes the daughter elements are not considered as part of the intake and if present must be considered on the basis of the rules for mixtures

LD_{50-30} is the dose required to kill 50% of the population in 30 days.

Thiols such as aminoethylisothiuronium (AET) and mercaptoethylamine (MEA) are effective as free-radical scavengers and can also form mixed disulfides to protect cellular sulfhydryls. They also can bind heavy metals, which in turn can inhibit cellular oxidation. Protection by the aminothiols cysteine, ME and AET as summarized by Langham (1967) (Ref. A.5.12) give a dose reduction factor of 1.6 to 2.0 for mice. However, the protection is not absolute, these compounds are highly toxic to man, the dose reduction factor decreases with increasing LET, offer little protection against chronic irradiation and are of doubtful value when delayed effects are considered.

2. Post-irradiation Treatment (Therapy)

The mechanisms of morbidity and death from high intensity radiation doses near the midlethal level are infection and hemorrhage, both of which to a large extent, are the result of bone marrow damage. The current approach to therapy is to treat the injury symptomatically (antibiotics, transfusions, etc.) and to use bone marrow transplants only if the symptomatic approach appears destined to fail. Bone marrow injections have given dramatic results in mice using isologous (same strain) marrow. The effect is lessened with homologous (different strains) and heterologous (different species) bone marrow. In dogs, the best results were obtained using autologous marrow, i.e., obtain marrow pre-irradiation and inject post-irradiation. In view of the immunological problems, the latter may be the most feasible method for space flight - provided adequate medical facilities including a physician are available.

A.5.4.5 Risk Considerations

1. Ground Personnel

Permissible doses have been necessarily changed as new data becomes available. The maximum permissible doses for all ground personnel as recommended by the Code of Federal Regulations (1968) Reference A.5.2 and the National Committee for Radiation Protection - (NCRP) (1971) in Reference A.5.3 is given in Table A-38. It is anticipated that the recommended doses by the NCRP will be used in the near future and therefore are recommended for use in the Space Base Study.

2. Flight Personnel

It is apparent that the limits suggested for ground personnel must be exceeded by flight personnel for any prolonged flight. Consequently, the NAS-NRC (Ref. A.5.12) has suggested that space radiation risks be evaluated in the following terms:

Table A-38. Dose Limits for Ground Radiation Workers

Currently in Use (10 CFR 20) Reference 4-4

Exposure	Condition	Dose (rem)
• WHOLE BODY - Head, trunk, active blood forming organs, gonads, lens of eye	Accumulated Quarterly	5(N-18 yr) 1.25
• SKIN - of whole body	Year Quarterly	30.00 7.50
• HANDS - and forearms, feet and ankles	Year Quarterly	75.00 18.75

Recommended (NCRP-39) Jan. 15, 1971 Reference 4-5

Exposure	Condition	Dose (rem)
• WHOLE BODY	Long Term Accumulated	5(N-18 yr) 5/year
• SKIN	Year	15
• HANDS, FEET & ANKLES	Year Quarterly	75 25
• FOREARMS	Year Quarterly	30 10
• OTHER ORGANS	Year Quarterly	15 5

(a) Immediate or early performance decrement (early responses) occurring within a few hours to one month following a major exposure.

(b) Progressively increasing performance decrement or serious loss of performance over long periods of flight as a result of an accumulating exposure (progressive injury to the blood-forming system).

(c) Probability of delayed or chronic radiation response that may require interrupting a planned series of flights and which may limit an astronaut's career.

Within each of these categories, the significant clinical symptomatology or responses must be defined on the basis of importance to crew safety and mission success. The relative significance of responses will be mission-dependent. The following suggestions may assist in identification of the important responses and in evaluation of their significance for each specific mission.

(a) Any amount of radiation exposure should be considered as potentially detrimental and, therefore, the exposure should be kept at a minimum consistent with the risk versus gain philosophy.

(b) Radiation guides should be set below the level that might result in an unacceptable probability of in-flight response capable of jeopardizing crew safety.

(c) Elapsed time between recurrent or repeat use of an individual or crew should take into consideration the nature and extent of previous exposure, the predicted exposure risk of the contemplated mission, and the degree to which mission success may depend on individual or crew experience.

(d) The dose or doses established for early effects automatically entails acceptance of certain probabilities of occurrence of generalized life shortening, leukemia, and other late manifestations.

(e) The radiation responses may be subdivided into "in-flight" and "post-flight" categories. Although this subdivision is somewhat arbitrary, it is time-dependent and may be important under special circumstances, for which certain higher risks may be acceptable if it is clear that the latent period for expression of injury will automatically cause the response to occur post-flight.

The NAS-NRC also suggests that DE in rems be replaced by reference equivalent space exposure (RES) in reference equivalent units (reu). The method of evaluation is the same as that employed in conventional radiation protection:

$$\text{RES (reu)} = \text{D (rads)} \times \text{QF} \times (f_1 \cdot f_2 \cdots f_n), \text{ where}$$

$f_1 \cdots f_n$ are modifying factors for adjusting the space-radiation exposure for relative differences in response per unit dose resulting from differences in "reference" and "space exposure" conditions.

Roth (Ref. A.5.29) in reference to J.E. Pickering gives the operational dose limits for SKYLAB:

(a) Planning Operational Dose (POD) - The dose which should not be exceeded without requiring a mission modification of some degree. The degree of modification will be a function of the magnitude of the excess dose and will be formulated by mission rules. This dose will be used for mission planning purposes to determine if proposed trajectories and time lines are acceptable.

(b) Maximum Operational Dose (MOD) - The dose which should not be exceeded without specific modification of the mission to prevent further potentially harmful in-flight response in terms of crew safety and post-flight response in terms of delayed radiation injury.

Provisional limits for POD and MOD as cited by Roth (Ref. A.5.29) are given in Table A-39.

Table A-39. Provisional Radiation Dose Limits Suggested for Preliminary Evaluation of a 30-60 Day Mission

TISSUE	DEPTH	POD	MOD
Skin	0.1 mm	2.5 rads/day	5 rads/day
Eye	3.0 mm	1.25 rads/day	2.5 rads/day
Bone Marrow	5.0 cm	0.6 rads/day	1.0 rad/day

More recent information from NASA-MSC (Ref. A.5.4) give the following limits for earth orbiting manned vehicles (Space Station/Base, Skylab, Shuttle). (See Table A-40).

The rate limit for radiation from all artificial sources should not exceed 0.15 rem/day, average.

Table A-40. Crew Radiation Limits (rem) Space Station/Base, Skylab, Shuttle

DEPTH	CAREER	YEARS	30 DAYS
Skin (0.1 mm)	2,400	240	150
Eye (3 mm)	1,200	120	75
Marrow (5 cm)	400	40*	25

*This limit may be doubled if the crewman is not exposed to any further radiation for the succeeding 12 months following the one year counted for exposure, i.e., no more than 80 rem in a 24 month period.

Except for marrow dose, the 30-day limit is identical to the MOD limit given in Table A-39. A revision to this data upon Rose (telecon 31 August 1970) recommendation from the National Academy of Sciences (Ref. A.5.7) reduces the skin and eye doses by about 1/2 and add a 3 cm (Testes) dose that will be about 1/2 the marrow dose (Table A-41). These reductions are in light of new evidence that low dose

rates are more dangerous than previously thought. These new data have been amended (Ref. A.5.8) to eliminate the testes dose as a primary design criterion. The testes dose is recommended to be applicable only where the possibility of oligospermia and temporary infertility are to be avoided. For most manned space flights, the allowable exposure accumulation to the Germinal Epithelium (3 cm) will be the subject of a risk/gain decision for the particular program, mission, and individuals concerned.

Table A-41. Anticipated Radiation Limits

CREW RADIATION LIMITS (REM)

AREA DEPTH	1 YR AVG DAILY	30 DAY	QUARTER	YEAR	CAREER
SKIN (0.1MM)	0.6	75	105	225	1200
EYE (3 MM)	0.3	37	52	112	600
*TESTES (3 CM)	0.1	13	18	38	200
MARROW (5 CM)	0.2	25	35	75	400

*NOT A PRIMARY DESIGN CRITERIA

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APPENDIX B

SPACE BASE PROGRAM REFERENCE MISSION

KEY CONTRIBUTORS

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E. E. GERRELS

APPENDIX B
SPACE BASE PROGRAM REFERENCE MISSION

B.1 GENERAL

The reference mission used in this safety study is presented in this Appendix and is briefly summarized below. The principal reference material used was that of the Phase A Space Base Definitions by NAR and MDAC (Reference 1 and 2).

The Space Base Mission is defined to begin with the arrival of the first flight hardware at the launch facility - the John F. Kennedy Space Center (KSC) and culminates in the End of Mission (EOM) disposal shutdown and/or recovery of program hardware. The program consists of several major pieces of hardware which comprise the Space Base or interface with and/or provide operational support. The program hardware is summarized in Table B-1.

Table B-1. Major Program Hardware

• <u>SPACE BASE VEHICLE</u> Zero-g Modules Artifical-g Modules Reactor Power Modules Extendable Booms Attached Experiment Modules Maintenance Facility Docking Ports Experiment Payload • <u>DETACHED "FREE FLYING" EXPERIMENT MODULES</u> • <u>LOGISTIC/BOOST VEHICLES</u> Saturn INT-21 S-II Kick Stage Space Shuttle Space Tug	• <u>OTHER INTERFACING VEHICLES</u> Reusable Nuclear Shuttle Orbital Propellant Storage Depot Comm. Relay Satellites • <u>GROUND FACILITIES</u> Launch Complex 39 Vehicle Assembly Building Mobile Launcher Nuclear Assembly Building Base Assembly Facilities Transport Vehicles Mission Control Center Range Recovery Equipment

For purposes of the study, the mission was subdivided into the four distinct phases shown in Table B-2.

A series of INT-21 launch vehicles will boost the Space Base Modules into a 500 km 55^{o} or 30^{o} inclination circular orbit where buildup operations take place. The INT-21 is also used to boost the reactor power modules to rendezvous with the awaiting orbiting Base. Space tugs will perform the final docking to the Base booms. After a brief checkout period, the power modules will be brought to operating power (50 kWe each) and full Base operations with the nominal 48-man crew are initiated. The ten year operational phase incorporates an extensive experimental program with periodic resupply of expendables, replacement hardware and the crew by the Space Shuttle.

The end of equipment lifetime or closeout of the Base is characterized by the safe disposal and/or recovery of the nuclear hardware.

B.2 TRAJECTORY/ORBIT PARAMETERS

The reference launch site is Launch Complex 39 at KSC. The INT-21 Space Base launch trajectory and orbit parameters used in the study are shown in Figure B-1 with orbital insertion of the payload occurring near Australia.

B.3 MISSION PHASE DESCRIPTION

The phase description presented is limited to the events associated with the nuclear system safety of the program. A general mission time-line is shown in Figure B-2. The build-up of the Space Base comprises activities of several mission phases and is assumed to encompass a 105 week period. Build up is followed by a ten year operational period during which a nominal 48-man crew conducts the experiment program in both zero-g and artificial-g environments.

B.3.1 PHASE 1.0 PRELAUNCH

The prelaunch phase, encompassing the period from arrival of the flight hardware at the launch facility through to completion of the countdown is separated into five subphases:

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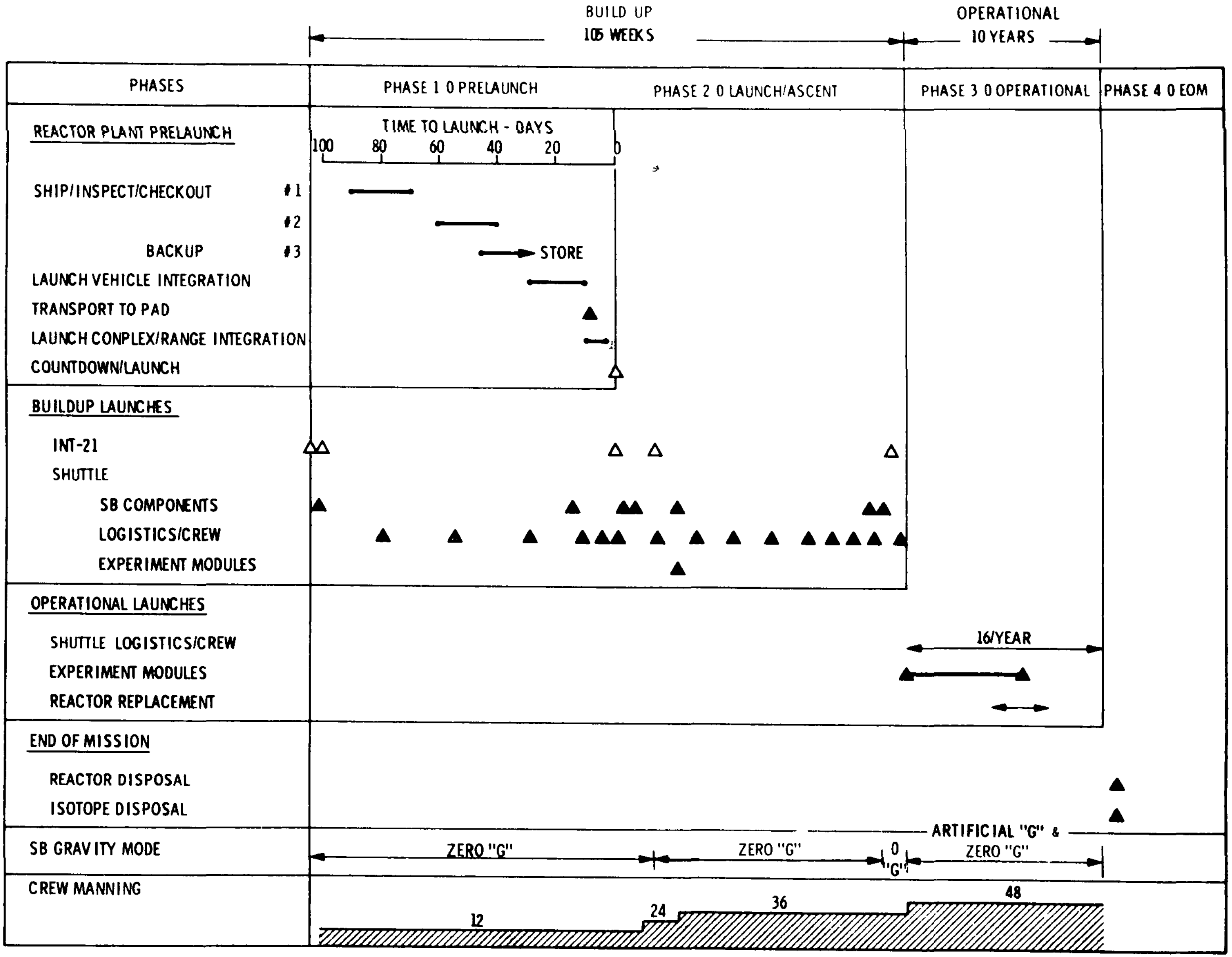


Figure B-2. Mission Timeline

1. Transportation
2. Receipt, Inspection, Storage
3. Checkout and Assembly
4. Integration
5. Countdown

B.3.1.1 Transportation

The transportation description of the Reactor Power Module (PM) at KSC is based on the assumption that the Power Module will be shipped to KSC in a nearly completely assembled configuration. All NaK loops will be filled before the final acceptance testing at the factory and will remain filled throughout all subsequent operations. The Power Module would arrive in an environmentally controlled shipping container which provides the proper monitoring equipment and ensures a clean, dry atmosphere. Previous operation of the reactor was limited to near zero power critical tests, therefore radiation levels around the reactor would be very low (maximum of 30 kW-hours).

The Power Module will be taken from the arriving airplane (or barge) by land transport to the Receipt and Inspection area (Nuclear Assembly Building) which is presently an undefined facility at KSC.

Three reactor Power Module units will be delivered, the third Power Module serving as the backup. Subsequent Power Module units will be delivered to KSC to serve as replacements during the mission. The first Power Module will be delivered approximately 90 days prior to launch, the second - 60 days, the third - 45 days. Transportation at KSC will be by truck/transporter trailer between the port of arrival, and Nuclear Assembly Building (NAB), the VAB and/or Complex 39.

The transportation of isotopes from the airport, trucking or rail facility will be by truck or automobile utilizing appropriate shipping and radiological procedures. Dose rates and integrity of the shipment are checked upon arrival and cooling provisions are maintained.

B.3.1.2 Receipt, Inspection and Storage

The transporter and Power Module will receive a comprehensive receiving inspection for proper configuration, visual damage and monitoring of instruments designed to record shock loads, environmental conditions such as humidity, air chemical composition and radiation. The transporter will be opened and an inspection made of the Power Module for visual damage, fluid leaks, system integrity and electrical harness and umbilical connections. Provision is made for the discharging and purging of the liquid metal systems such that if a leak were detected, the system could be safed for shipment back to the factory. Reactor control safety devices will be checked. Consideration is given to the use of the transporter during all phases of inspection, checkout and storage; providing a universal piece of hardware equipped with proper status and safety instrumentation.

Storage of three Power Module units is to be provided with storage times of at least one year. In addition to the two Power Module units on the Space Base in orbit, a minimum of two replacement Power Module units are stored in a ready condition during the operational mission. Routine airborne and surface radiation and contamination measurements are made while the hardware is in storage. Periodic (180 days) power module verification checks are also made. Preparation for storage will involve enclosing the entire Power Module within the transporter under a protective cover of dry gas (argon or N_2). Purging of the container is required whenever the enclosure is opened. Therefore, status monitoring provisions will be made through the container walls to enable periodic checkout without opening the enclosure.

Isotopes undergo a receiving inspection which includes a check of integrity, radiation, gas sampling and temperature. Cooling requirements must be met under all conditions. Isotopes are stored in their shipping containers within the designated facility until their use on the Space Base or in checkout operations. (The provisions and procedures for an Isotope Brayton Power System are similar to that proposed in the Separately Launched Power Module Study Document - Reference 3.)

B.3.1.3 Checkout and Assembly

Prior to integration with the booster or placement in storage, a series of subsystem verification tests will be performed to assure the integrity and functional operation of the Power Module. The nuclear facility utilized for storage would also serve as the checkout and assembly area. Consideration is given to the performance of tests on the transporter in conjunction with a series of semi-portable test equipment. Continuity tests will be given electrical connections and harnesses. Pressure and leak tests will be made and the Power Module coolant system will be operated to verify functioning of the PCS, valves, TEM pumps, and liquid lines. Minimum loop flow tests will be made which will require the use of strip heaters to provide sufficient thermal energy for operation of the NaK pumps.

Individual reactor control drums will be checked to verify operation and response characteristics and safing devices checked and installed. No criticality test is made. A Power Module systems test will then be performed where booster and spacecraft interface electrical signals can be sent, received and sequenced for prelaunch and in-flight simulation. Mechanical and electrical interfaces will be checked to ensure compatibility with the launch vehicles and spacecraft. Booster interface rings and shrouds are used to check for mechanical interface conformance. As in the case of all subsequent tests, nuclear safety regulations are to be followed. Materials and personnel within the prescribed test areas must be controlled. Actual testing within the facility will comprise a minimum of ten days. After prelaunch tests the Power Module will be prepared for transportation to the VAB or Mobile Launcher (ML) for integration with the launch vehicle or put in interim storage. This operation includes the addition of the module radiator shrouds and the installation of special instrumentation, safing and ordnance devices.

B.3.1.4 Integration

The nature of the launch vehicle integration tests to be performed are dependent on the selection of the launch vehicle and facility safety constraints. The reference baseline launch vehicle is the INT-21. The possibilities exist of integrating the power module within the VAB or performing all integration tests at the Launch Pad Complex 39. In either case, the Power Module should be scheduled as late in the sequence as possible. For purposes

of the safety analysis, integration of the Power Module units within the VAB is considered. Launch vehicle integration involves the mating of the hardware and the performance of those interface and combined systems tests to assure launch readiness. Countdown demonstrations are performed and certain post-launch conditions are simulated such as Power Module separation, umbilical disconnect and instrumentation and power transfers.

Initial mating/loading checks with the booster and the handling devices will be performed utilizing a dummy payload. Electrical and mechanical interfaces are simulated. A simulated systems launch readiness and countdown test is performed with this configuration to ensure compatibility of instrumentation, environmental and support systems.

At approximately T-27 days, the reactor Power Module is transported to the VAB or the launch pad for mating to the INT-21 launch vehicle on the Mobile Launcher. Electrical and mechanical connections are made, the launch shroud is installed and combined systems tests are performed. Separation, umbilical disconnect and instrumentation tests are made, culminating in a flight readiness demonstration and simulated countdown. A controlled environment is provided.

Isotopes are contained in experiment and payload accommodation modules of the Space Base. The baseline does not identify the placement of isotopes in the Space Base Modules. However, certain experiments will contain isotopes and tracer elements and due to the confinement of some hardware, the necessity may exist for small quantitites of isotopes to be on-board throughout the VAB activities. Isotopes possibly contained within thermal control subsystems would consist of small capsule heaters of 5 to 50 watts. Where possible, the isotope installation should be scheduled for the launch pad. Environmental control/cooling provisions will be maintained.

At approximately T-8 days the Space Vehicle complete with Reactor Power Module(s) is delivered to Launch Complex 39 via the Mobile Launcher Crawler. The shroud is maintained in position around the Power Module at all times. Power Module instrumentation monitored includes umbilical and separation circuit connections, radioactivity, environmental conditions

and control circuit continuity. Telemetry radio frequency interference and range verification tests are made. Simulated countdown, propellant loading, and pressure tests are made.

B.3.1.5 Countdown

The countdown is initiated on the INT-21 at T-2 days where flight readiness and functional checks are given major subsystems. Special cryogenic and spacecraft fuel tanks are loaded. Ordnance (including disposal rockets) are installed (T-15 to T-10 hours) prior to launch vehicle cryogenic loading. Pad accessibility is very much limited at this point. (The installation of an isotope-Brayton Power System should occur prior to this time period.) Continuous monitoring of systems is provided throughout the final phases of the countdown. The terminal countdown is initiated at T-1 hour with the completion of all flight readiness checks and the propellant loading sequences. An automatic sequence for the start of the engines is initiated at T-187 seconds. Swing arms are around the vehicles until the automatic sequence is initiated, however, the removal of some upper service arms would be permissible at an earlier hour to afford abort potential. This phase terminates with ignition of the S-IC booster engines.

B.3.2 PHASE 2.0 LAUNCH AND ASCENT

The Launch and Ascent Phase is assumed to begin at lift-off and terminate with the docking of the payload. Four subphases are identified:

1. Launch
2. S-IC Boost
3. S-II Boost
4. Rendezvous and Docking

B.3.2.1 Launch

The INT-21 launch vehicle will be used to boost the reactor Power Module(s) to orbit from Launch Complex 39. The Power Module is dormant during the Launch and Ascent Phase. However, a small amount of power may be supplied from a temporary source to provide a minimum flow of NaK in the coolant loops. This flow prevents localized freezing of the NaK during ascent and prior to reactor startup.

The Space Base Mission requires insertion of the payload into a 500 km (273 nm) circular orbit inclined 55 degrees to the earth equatorial plane. The launch azimuth for this orbit is 46 degrees, measured east of north, as a result of current range safety requirements at the Eastern Test Range (ETR). This azimuth is not compatible with the desired orbit inclination, therefore, a plane change of 6-degrees (S-II stage yaw) is employed when the impact points pass Newfoundland, providing a new azimuth of $\sim 40^{\circ}$. A typical INT-21 flight sequence is shown in Table B-3. (Ref 4, 5).

B.3.2.2 <u>S-IC Boost/Ascent</u>

The reference trajectory assumes a Hohmann Transfer technique with a 185 x 500 km orbit circularized to 500 km.

At first motion, the launch vehicle begins a rise of 138 meters to clear the launch umbilical tower. Following tower clearance a pitch program induces a turning rate on the launch vehicle. The pitch program continues until 41 seconds after first motion. At this time the launch vehicle begins a gravity-tilt profile which continues until tilt arrest at 153 seconds after first motion. Tilt arrest is maintained during S-IC/S-II staging and continues through the remainder of the atmospheric portion of flight.

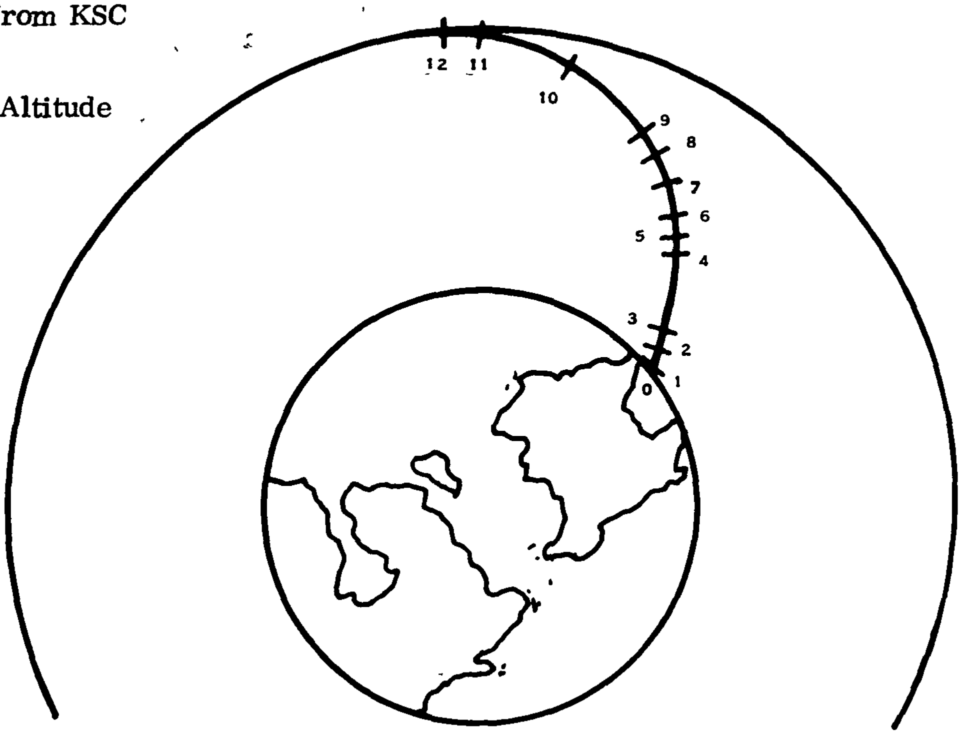
The fueled operations of the prelaunch and early boost phases of the mission present conditions most conducive to fire and explosive accidents. No payload abort or ejection hardware is provided.

Maximum dynamic pressure occurs at $\sim$ 75 seconds after lift-off and maximum axial acceleration is limited to $\sim$ 4.5 g by an early center engine cutoff.

B.3.2.3 <u>S-II Boost/Ascent</u>

The S-II boost, initiated at $\sim$ 160 seconds, delivers the payload to either the final circular orbit or to a parking orbit (185 x 500 km). The payload shroud is jettisoned at $\sim$ 195 seconds after first motion. Atmospheric flight is terminated $\sim$ 4 seconds later. Vacuum flight and the Iterative Guidance Mode (IGM) are initiated at $\sim$ 199 seconds with the IGM providing both

Table B-3. Sequence of Events for Typical INT-21 Launch from KSC



Seq. No.	Event	Time (Sec)	
		Max Payload	86t Payload
0	Ignition	-9	-9
1	Lift-Off	0	0
2	Initiate Tiltover	11	12
3	End Tiltover-Begin Gravity Turn	41	35
4	S-IC Center-Engine Cutoff (CECO)	139	149
5	S-IC Burnout	157	161
6	S-IC-SII Separation	159	163
7	S-II Ignition	161	165
8	Interstage Jettison	189	
9	Shroud Jettison	195	193
10	S-II-CECO	458	
11	Guidance Cutoff	547	
12	Orbit Insertion	557	544

pitch and yaw steering commands during the remainder of the ascent to orbit. The engines are subsequently cut-off and the S-II stage is separated. Two perigee passes are allowed before the S-II kick stage fires and circularization and final orbit adjustments are made. The S-II/IU kick stage is initially loaded with about 5.4 t (12 klb) of hypergolics. Firing time for the kick stage can range from 3 to 15 minutes.

B.3.2.4 Rendezvous and Docking

It is assumed that a "Space Tug" will be used to rendezvous and dock with the reactor Power Module and subsequently perform the final rendezvous and docking operations with the Space Base. The tug is considered of limited capability and can fit within the Shuttle cargo bay when in a 12-man delivery configuration. Its mass is ~ 9.7 t (21.5 klb) with a 2 man crew and usable propellant of ~ 5.5 t. Maximum closing velocities are not to exceed about 1.5 m/sec (5 ft/sec) as shown in Figure B-3.

B.3.3 PHASE 3.0 ORBITAL OPERATIONS

The orbital operations phase consists of a 105 week Space Base build-up period which involves several INT-21 and Space Shuttle launches and carries through the 10 year operational mission.

The five subphases identified for the orbital operations are:

- Orbital Buildup
- Checkout
- Start-up
- Operational Mode
- Contingency Operation

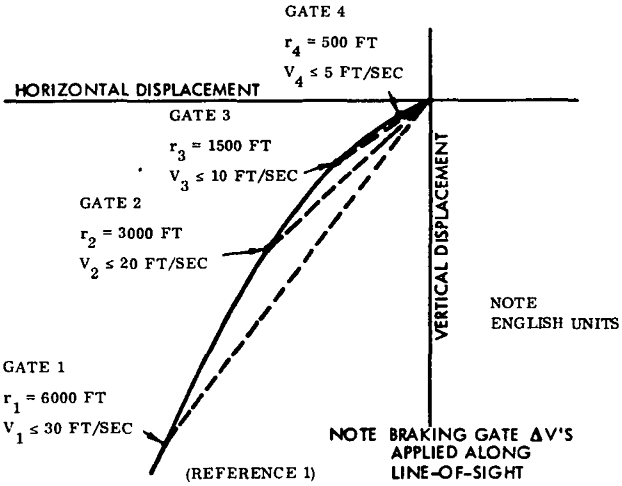


Figure B-3. Terminal Rendezvous Braking Gates Relative to Target

B.3.3.1 Orbital Buildup

The zero g core modules are assembled first during an ~ 52 week period, after which the reactor Power Modules are launched and docked to the Space Base power module booms. Docking is assumed to take at least 50 minutes with about 30 minutes spent by the tug near the power module boom interface. Docking of the PM with the Base will be followed by a manual IVA (2-man operation) connection of the electrical and control circuits at the boom interface. At the time of installation of the reactor power modules the Base would be manned by a minimum of 24 crewmen. The initial manning of the Base is accomplished by 12 man-Space Shuttle launches. Full artificial g habitation and zero g core operation with a nominal crew of 48 is achieved after 105 weeks. Normal crew rotation by the Space Shuttle will be every 90 to 180 days.

B.3.3.2 Checkout

Prior to delivery of the reactor Power Module, consideration should be given to the launch of a simulated Power Module for purposes of proving rendezvous and docking procedures (prior to T + 52 weeks). Following the docking of the operational PM's, the Tug or Space Shuttle will perform a fly-by inspection for exterior damage. The PM circuits are monitored in the control room and continuity checks are made. Power Module systems are activated with auxiliary power. Power Module system functional tests are made and instrumentation systems are verified operable. Control system operation is verified, and interlocks (if provided) are removed to allow control durms to assume pre-startup positions. Functional tests of the power distribution and conditioning systems are performed with auxiliary power. These Power Module readiness tests should require less than four hours for each reactor and would be performed from the control module. When readiness is achieved, the Power Module booms are extended into the normal operating position.

B.3.3.3 Start-up

The initial start-up of the individual nuclear PM units will be performed immediately after checkout and communications tests. The startup sequence is performed after the booms have been extended with the thermal shrouds around the radiator. The automatic sequence is initiated from the control room with the sending of the reactor coded and sequenced start

command. A controlled speed stepping sequence individually single steps the drums in sequential order. As criticality approaches, as planned into the program, the stepping speed is reduced, the reactor brought slowly through criticality and up to operating temperature and power, as described in Section 2. Current operation conditions are controlled by temperature measurements of the working fluid. The reactor is not designed to be load following. It will operate at the designated 330 kWt condition regardless of the electrical power drain. Power for these start-up operations comes from the Space Base auxiliary power system. The thermal shroud is incrementally retracted as fluid temperature is attained. The entire start-up sequence requires about 4 hours, with an additional 4 hours allocated for system stability. Start-up of both reactors can be accomplished within a 12-hour period.

Switch-over from auxiliary to reactor power will allow the reactors to assume the electrical load of the Space Base and the initiation of additional experimental activities. Roll-up of the solar array power system is accomplished after stabilization is achieved. Full power operation of over 50 kWe is not required immediately but is built up as the Base is expanded. (Power requirements are increased from approximately 40 kWe initially to a nominal 100 kWe when fully operational capability is achieved. During this entire time period, each reactor is operating at 330 kWt, however adjustments in the gas management system can be made for long off-power operations.

B.3.3.4 Operational Mode

Orbital operations of the Space Base actually are initiated with the arrival of the first 12-man crew in orbit T + 2 days into the flight program. Completely operational orbital operations of the nominal base are not initiated however, until the 48 crew and full complement of Base modules are in orbit.

The first $\sim$ 110 weeks of the mission are operationally unstable in that conditions and operational routines are changing. Crew living quarters are expanded with the addition of habitation modules and the experiment program increases as sub satellites are launched and experiments are activated within the basic core modules. At approximately the 110th week so called "stable operations" exist.

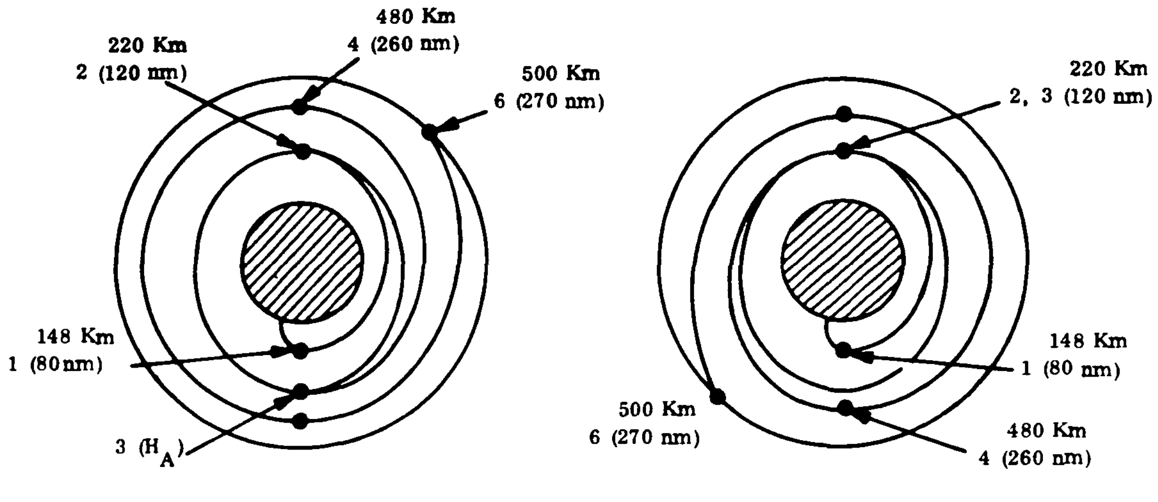
During the operational mode the nominal Shuttle logistic mission frequency is assumed to be 16 per year. A Shuttle ascent profile is shown in Figure B-4. (Reference 1).

Crew types expected on such a mission are listed in Figure B-5 (Reference 6). An estimated averaged time and location of the crew throughout a typical day is also shown in Figure B-5 for a 48 and a 60 man crew.

Additional operational activities during this phase include logistic support, experiment support, routine maintenance, and occasional support of the Resusable Nuclear Shuttle (RNS) and the Orbital Propellent Storage Depot. A major logistic requirement is the replacement of all or portions of the power module. For purposes of this baseline, it is assumed that replacement power modules or their components are launched on the Shuttle (recognizing present size incompatibilities). Replacement is considered feasible with the other power module operating. Normal power module replacement is anticipated every 5 years. Replacement of the Brayton Power Conversion System Module can occur after 2.5 years.

During normal operations, only limited monitoring of the PM is required which can be done from the Base or the MCC. These operations can be performed periodically or on command by an onboard checkout and monitoring system. A degree of fault isolation will be provided via instrumentation to enable the crew to rapidly diagnose and correct the situation. The most important function of the onboard systems is to monitor life and mission-critical functions continuously to provide advanced warning and allow for maintenance preparations. Immediate and in some instances automatic corrective actions such as PM shutdown should also be provided if conditions arise which cannot wait for crew intervention.

Planned PM shutdowns require several steps including the activation of the back-up solar array power system. The shutdown commands to the reactor cause the control drums to step outward at the 3-second stepping rate. The neutron radiation drops to about 1 percent in 3 minutes at this rate and in about an hour the reactor coolant temperature will have dropped to below 425°K (300°F). The reactor radiator thermal shrouds are then repositioned around the radiator to prevent NaK freezing.



MODE 1

MODE 2

KEY:
1. 148 X 220-Km ORBIT INSERTION
2. PHASING ORBIT INSERTION MANEUVER
3. HEIGHT ADJUSTMENT MANEUVER
4. COELLIPTIC MANEUVER
5. TERMINAL PHASE INITIATION
6. RENDEZVOUS

ΔV (PHASING ORBIT INSERTION TO TERMINAL PHASE INITIATION = 170 M/SEC

$\Delta T_{1,2}$ = 44.1 MIN

$\Delta T_{3,4}$ = 45.8 - 47.1 MIN

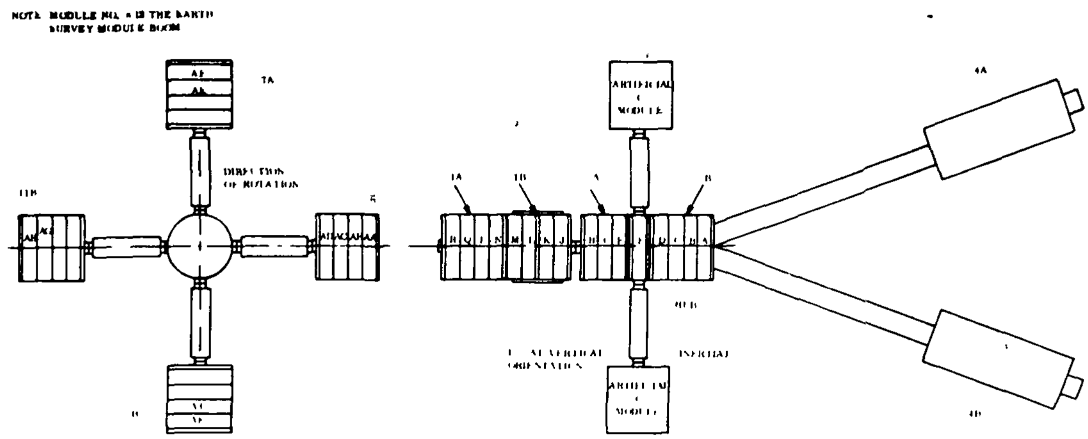
$\Delta T_{4,5}$ ~ 47.1 MIN

$\Delta T_{5,6}$ = 36.7 MIN

Shuttle Ascent Mission Timelines

Event	0.5 Rev in Phasing Orbit		16.5 Rev in Phasing Orbit	
	Event Duration (hr)	Cumulative Time (hr)	Event Duration (hr)	Cumulative Time (hr)
Boost to 148 x 220 km Orbit	0.170	0.170	0.179	0.170
Coast to Apogee	0.735	0.905	0.735	0.905
Phasing Orbit Coast	0.741	1.646	25.212	26.117
Transfer to Coelliptic Orbit	0.786	2.432	0.764	26.881
Coast in Coelliptic Orbit	0.786	3.218	0.786	27.667
Terminal Phase Transfer	0.611	3.829	0.611	28.278

Figure B-4. Shuttle Ascent Profile (Reference 1)



MODULE	DECK	48-MAN CREW (Average Number)	60-MAN CREW (Average Number)
2B	A	.10	.10
	B	1.20	1.25
	C	.95	1.00
	D	.15	.15
2A	E	.04	.04
	F	.06	.06
	G	.30	.30
	H	.14	.14
1B	J	1.70	1.75
	K	3.20	3.30
	L	3.50	3.60
	M	3.50	3.80
1A	N	.65	.70
	P	.70	.75
	Q	.45	.50
	R	2.20	2.35
11A	AA	.10	.10
	AB	1.00	1.08
	AC, AD	22.00	29.00
7A	AE	.90	.95
	AF	.65	.70
11B	AG	2.30	2.40
	AH	1.10	1.15
7B	AJ	.75	.80
	AK	.65	.70
	Transfer	3.50	3.65
	Hub	1.50	1.60

Figure B-5. Typical Day Averaged Crew Locations

B.3.3.5 Contingency Operations

A number of unplanned situations can occur during the in-orbit operational phase. Contingency plans must be available to minimize the effect on the mission and the crew. Some of the identified contingencies are listed below.

1. Loss of one power module - necessitating operation from the other at either 600 kWt (100 kWe) or at normal power.

2. Shuttle or support hardware malfunction not allowing a replacement of the crew in designated time period. This could result in an additional 12 men in orbit for several weeks.

3. Forced closure of one or more modules due to equipment damage or contamination.

4. Complete zero g operation of the Base.

5. Failure of total reactor power system necessitating operation of the Base on back-up power of ~ 18 kWe. Rapid return of a number of the crew may be required (0.6 kWe assumed for support of each crew member).

6. Inability to dock logistic vehicles and crew resupply modules.

7. Loss of pressure in pressurized modules.

8. Loss of cooling for isotope heat sources.

9. Collisions of interfacing vehicles or other sizeable objects with the Base and or power modules.

10. High intensity solar flare.

11. Loss of internal and/or external communications.

12. Loss of reactor power module computer control.

13. Failure to maintain Base stabilization.

14. Environmental malfunction or contamination.

15. Rapid unplanned Base abandonment (close-out).

B.3.4 PHASE 4.0 END OF MISSION

The end of mission or end of life of particular hardware, two separate operations are involved: (1) Power Module Disposal or Recovery and (2) Space Base Closeout and recovery of nuclear hardware.

B.3.4.1 Reactor PM Disposal

At the end of the normal lifetime of the reactor or after any accident which permanently or severly damages the reactor or power conversion system, the PM will be boosted into a nominal 990 km (535 nm) circular orbit where the fission product inventories will be allowed to decay to acceptable levels over a minimum 250 years prior to eventual reentry. The sequence of events include an on-board checkout of the Disposal System (Reference 7) and PM shutdown status. After shutdown is confirmed and systems have been verified the PM is separated from the Base at approximately 0.6 m/sec (2 ft/sec) by a spring eject system. The PM guidance and control system will orient the PM for the disposal rocket burn. When the preselected separation distance of several kilometers is attained, the rockets are fired by remote control from the Base, the MCC providing a backup capability. Alternatives to the high earth orbit disposal approach are identified in Section 7 and in Volume IV Part 1.

B.3.4.2 Space Base Closeout

The termination of the Space Base Mission either planned or unplanned (possibly caused by malfunctions) will result in its eventual return into the earth's atmosphere. Power modules are planned for separate disposal but isotopes on-board the Base must be handled separately. It is assumed that a systematic close down of the Base is attempted which includes shutdown and possible return of certain hardware including the return of radioisotopes by the Shuttle. Failures in this procedure could result in re-entry of some of this hardware.

References

1. "Space Base Definition", SD 70-160, MSC-00721, North American Rockwell, July 1970.

2. "Space Base Concept Data", MDC G0576, McDonnell Douglas Astronautics Company, June 1970.

3. "Study of Separately Launched Multi-Use Space Electrical Power System", GESP-7007, General Electric Company, November 1968.

4. "Operational Flight Analysis-INT 21-Task 23", OFA-H-760, Boeing Company, October 1970.

5. "Preliminary Reference Design Document-Reactor", Volume II, MDC G0744, McDonnell Douglas, January 1971.

6. "Earth-Orbiting Space Base Crew Skills Assessment", NASA TMX-1982, Manned Spacecraft Center, April 1970.

7. "Post Operational Safety of Reactor Power System for NASA Space Station", AI-AEC-MEMO-12917, Volume V, June 30, 1970.

APPENDIX C

SPACE BASE POWER MODULE FAULT TREES

KEY CONTRIBUTORS

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APPENDIX C
SPACE BASE POWER MODULE FAULT TREES

C.1 GENERAL

The purpose of this Appendix is to present the preliminary fault trees for the Reactor Power Modules in the Space Base Mission.

Fault trees are constructed by showing all possible faults which either singly or in concert result in a given undesired event. Each of the contributing faults are, in turn, similarly developed. This sequence is continued until conditions are reached which cannot or need not be further developed. Contributing faults are connected via logic gates which indicate whether any one of the lower level faults is sufficient to cause the next higher level fault to occur (the "or" gate), or whether they are all necessary and sufficient to cause the higher level fault (the "and" gate). In this way, a hierarchy of faults is developed with the primary undesired event appearing at the apex of the fault tree. In this case the primary faults are the nuclear hazards developed during the analysis.

1. Release of fission products
2. Release of activated materials
3. High radiation field around reactor, and
4. High radiation field around power system components

Figure C-1 shows the various symbols used in constructing the fault trees. The nuclear hazards are identified by diamonds, the ellipses denote safe conditions, and the rectangles indicate primary accidents.

C.2 FAULT TREES

Figures C-2 through C-5 present the preliminary fault trees for the four basic nuclear hazards down to the level of unsafe conditions. Figures C-6 through C-22 develop each of the unsafe conditions down to the primary accidents that caused the unsafe conditions. The

following pages are devoted to a brief explanation of the preliminary fault tree construction for each of the nuclear hazards.

C.2.1 RELEASE OF FISSION PRODUCTS

Five basic unsafe conditions have been identified which result in a release of in-core fission products. It should be emphasized that none of these unsafe conditions can arise from a single failure of the reactor power module. For a release of fission products to occur, the fuel element cladding must be breached or ruptured allowing the fission products to be released from the fuel element together with an external failure of the reactor power system thus providing a means for the fission products to escape to the external environment. The five unsafe conditions that have been defined for the release of fission products are:

1. Disassembly or destruction of the reactor accompanied with damaged or destroyed fuel elements.
2. Release of fission products to the primary coolant and a breach of the primary loop.
3. The presence of fission products in the intermediate loop with a breach of the intermediate loop.
4. The presence of fission products in the secondary or PCS gas loop with a breach of the loop.
5. The presence of fission products in the primary heat rejection loop with a breach of the loop.

Figure C-6 shows the primary accidents that can result in disassembly of the reactor with fission product release. Primary blast and/or fragmentation refers to the explosion of the launch vehicle (INT-21) with the subsequent release of the fission products that have been generated during the zero power criticality testing prior to shipment to KSC. Secondary blast and/or fragmentation refers to either a collision during transportation and handling prior to launch or a collision with a meteor, logistic vehicle, satellite, or orbital debris while in orbit. Reactor disassembly upon earth impact can occur following orbital or sub-orbital re-entry (reactor impact at terminal velocities) or possibly from a fall from atop the launch vehicle. Meltdown leading to a release of fission products can arise from an external fireball or from excessive reactor core temperatures.

A breach of the primary reactor loop (Figure C-8) can be a breach of the reactor pressure vessel, primary piping, primary heat exchanger, NaK accumulator, or primary pump assembly. This would result in a release of the activated primary coolant which in this case contains fission products released from the fuel elements.

In order for fission products to be released to the intermediate coolant loop, a clad failure must first occur followed by an internal failure of the primary heat exchanger which allows primary coolant containing the fission products to leak into the intermediate NaK coolant loop. If the intermediate loop is subsequently damaged or has previously been damaged but has gone undetected, then the fission products may be released external to the reactor.

With fission products present in the intermediate loop, there is a possibility that they could get into the secondary or gas loop via a damaged heat source heat exchanger (HSHX). If the leak is large enough to allow considerable amounts of NaK to enter the gas loop, the effect of this liquid metal striking the turbine blades immediately downstream of the heat exchanger could result in severe mechanical damage that might breach the loop. On the other hand, if the leak in the HSHX allows only droplets of liquid metal to penetrate the gas loop, the result might still be mechanical damage to the loop, but over a longer period of time (increased corrosion rates, for instance). Depending on whether the loop were damaged either by the mechanical damage caused by the NaK or by some other means, the fission products could then be released to the surrounding environment.

Still another possible means of fission product release is a damaged heat rejection loop (HRL). For fission products to get into the HRL, the copper bus between the cold and hot throats in the primary thermoelectric pump assembly must be damaged allowing the primary coolant containing the fission products to leak into the heat rejection loop. A damaged HRL will then allow the fission products to escape to the external environment.

C.2.2 RELEASE OF ACTIVATED MATERIAL

Eight unsafe conditions have been defined for the release of activated materials (Figure C-3). Five of these are identical to those just discussed for the release of fission products except

that for this case, the fuel element cladding is not breached and there is no release of fission products. The activated materials that are of interest are (a) bare fuel elements, (b) activated structural debris, (c) activated coolant, and (d) activated vapors, gases, and particulates. The destruction or disassembly of the reactor may result in the release of all of these activated materials, whereas a breach of the primary loop will result only in a release of activated coolant.

The remaining three unsafe conditions not previously discussed are (a) disassembly of the power conversion system either upon re-entry, accidental collision, earth impact, etc., in which all or any of the following activated materials could be released: activated structural debris, activated coolant, and activated vapors, gases, and particulates; (b) damaged LiH reactor shield resulting in the release of radioactive tritium that has built up in the shield during the normal operation of the reactor; and (c) the diffusion of radioactive tritium through an undamaged LiH shield. Since tritium is primarily an internal exposure problem resulting from its inhalation or ingestion in contaminated food and water, it is not an orbital operational hazard since the tritium would escape to space and not enter the Space Base internal environment.

C.2.3 HIGH RADIATION FIELD AROUND REACTOR

Three unsafe conditions resulting in a high radiation field around the reactor have been identified (see Figure C-4). They are:

1. A reactor excursion either while operating or shutdown, in orbit or at ground level.
2. A damaged reactor shield while the reactor is either operating or shutdown, in orbit or at ground level.
3. A quasi-steady state operating reactor, ground level.

The first two unsafe conditions should be rather self-explanatory. A reactor excursion (destructive or nondestructive) can result in a high radiation field produced by the prompt radiation either prior to launch, during normal reactor operations in orbit, or after earth

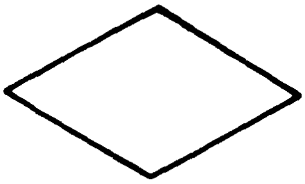
impact following reentry. Likewise, a damaged reactor shield can result in a high radiation field around the reactor caused by prompt radiation during normal operations.

Quasi-steady state critical operation refers to the reactor periodically going critical and subcritical due to water surging in and out of the reactor core. This can occur after water impact and immersion, and also after land impact and subsequent immersion in a water filled crater.

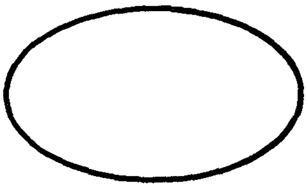
C.2.4 HIGH RADIATION FIELD AROUND POWER MODULE COMPONENTS

This last nuclear hazard (see Figure C-5) is concerned only with the normal in-orbit operation of the reactor. Four unsafe conditions have been identified, two of which require the presence of fission products and/or activated coolant in either the intermediate coolant loop or the heat rejection loop. Since both of these loops are external to the reactor shielding, a radiation field will be present due to the radioactive decay of the fission products and/or the activated coolant.

LIST OF FAULT TREES

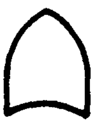


NUCLEAR HAZARD



UNSAFE CONDITION

PRIMARY ACCIDENT



"OR" GATE. ANY ONE OF THE CONTRIBUTING FAULTS ARE BY THEMSELVES SUFFICIENT TO CAUSE THE NEXT HIGHER FAULT.

"AND" GATE. ALL CONTRIBUTING FAULTS ARE NECESSARY FOR THE NEXT HIGHER FAULT TO OCCUR.

TRANSFER GATE. THE NUMBER REFERS TO THE FIGURE WHERE THE BRANCH IS FURTHER DEVELOPED.

Figure C-1. Legend of Fault Tree Symbols

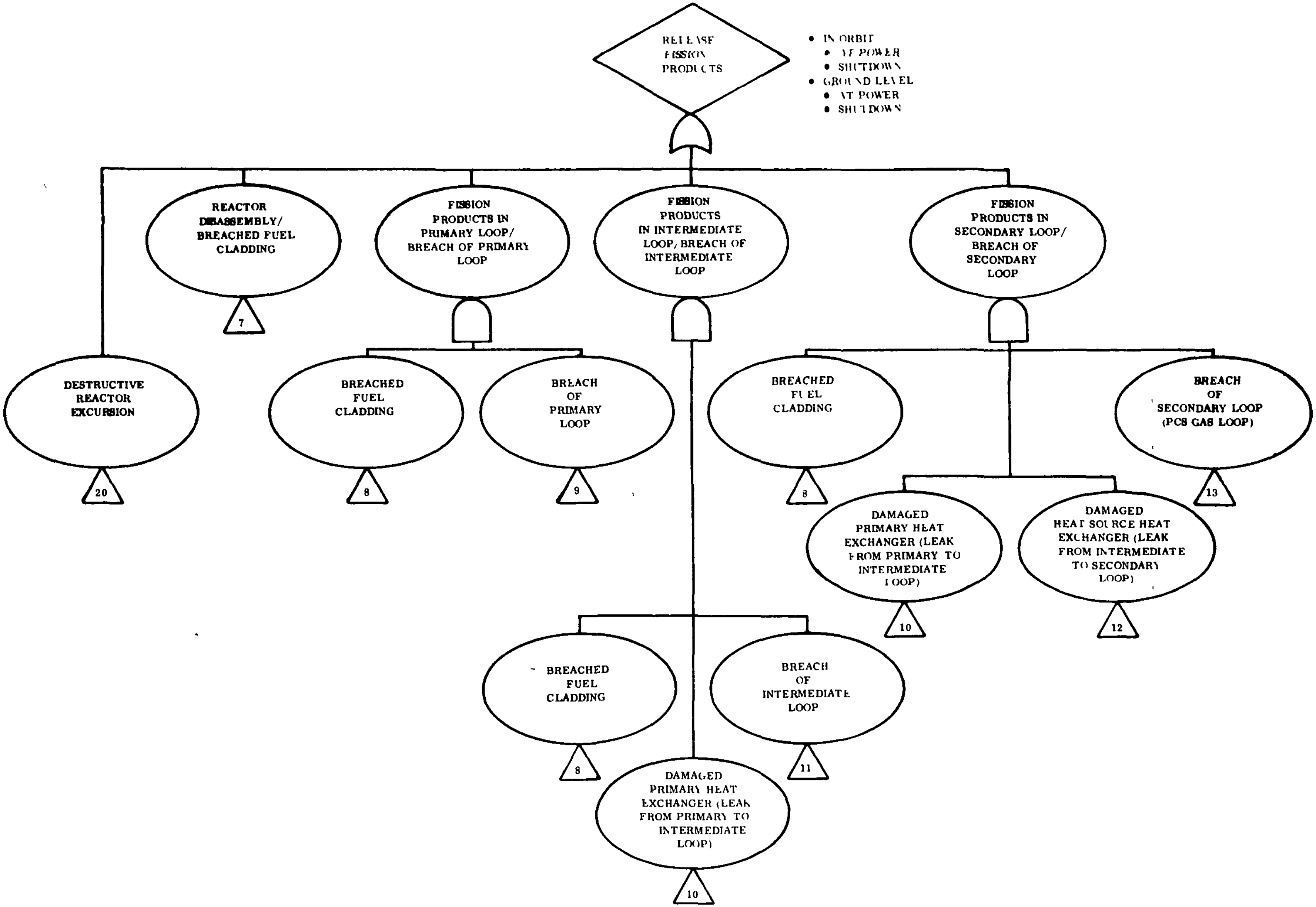


Figure C-2. ZrH Reactor Power Module Fault Tree
(Release of Fission Products)

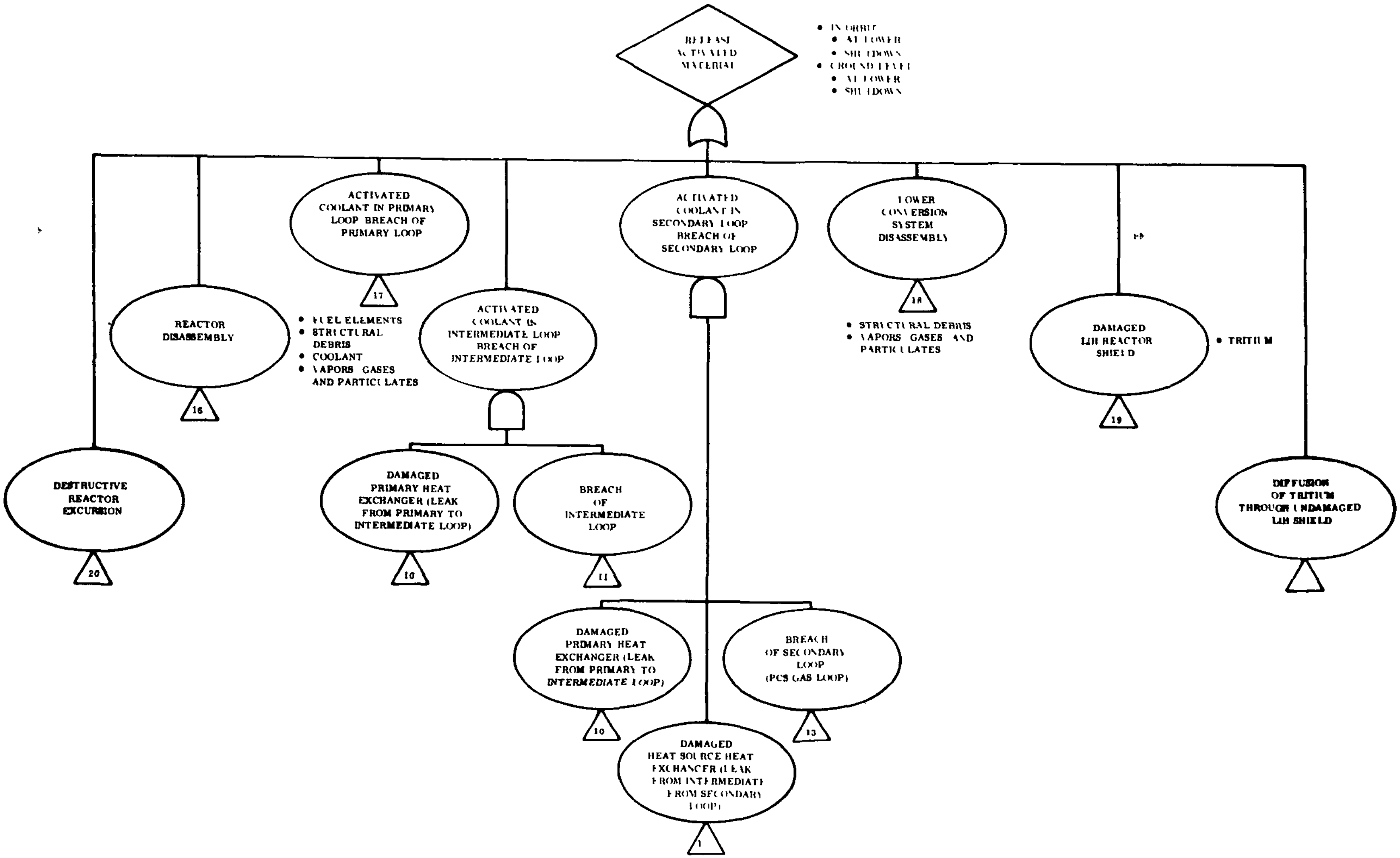


Figure C-3. ZrH Reactor Power Module Fault Tree
(Release of Activated Material)

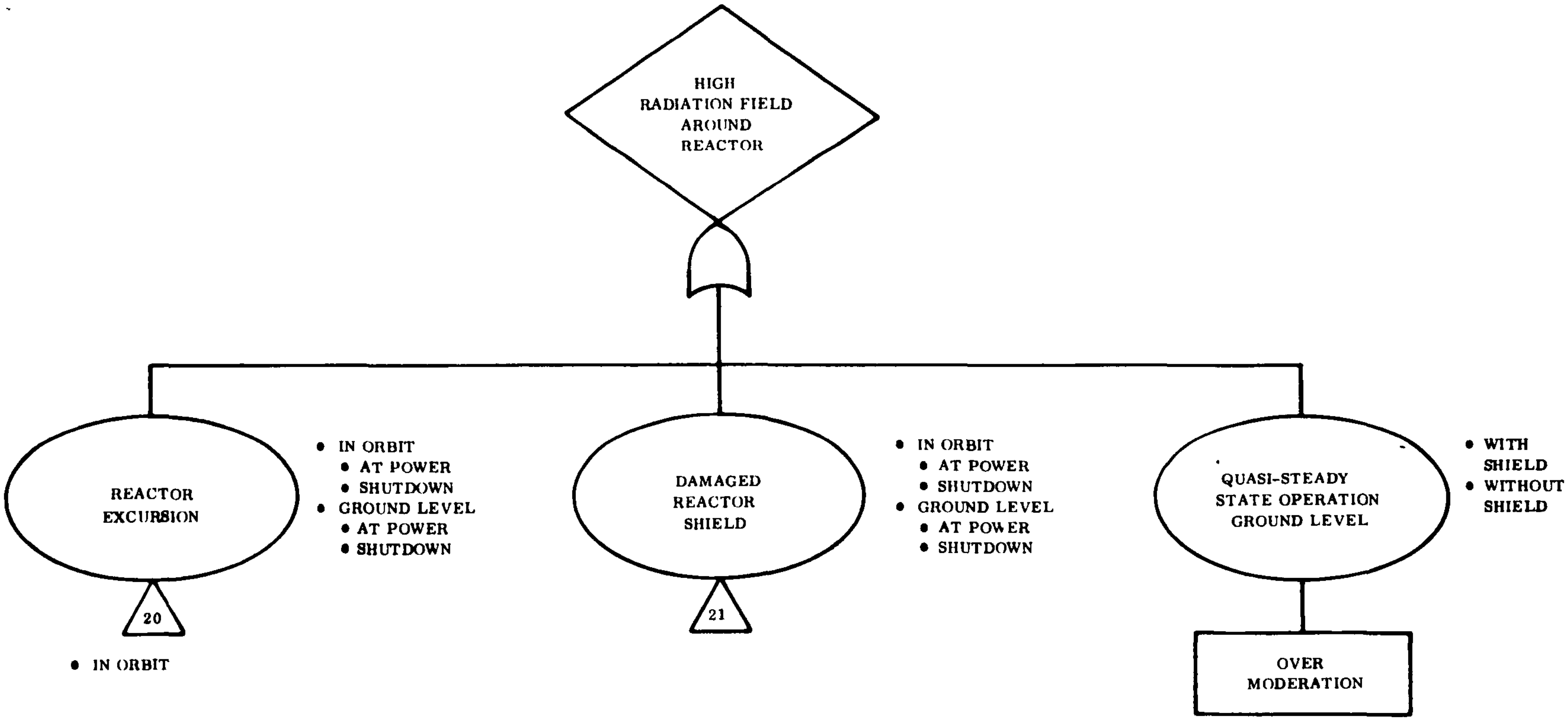


Figure C-4. ZrH Reactor Power Module Fault Tree
(High Radiation Field Ground Reactor)

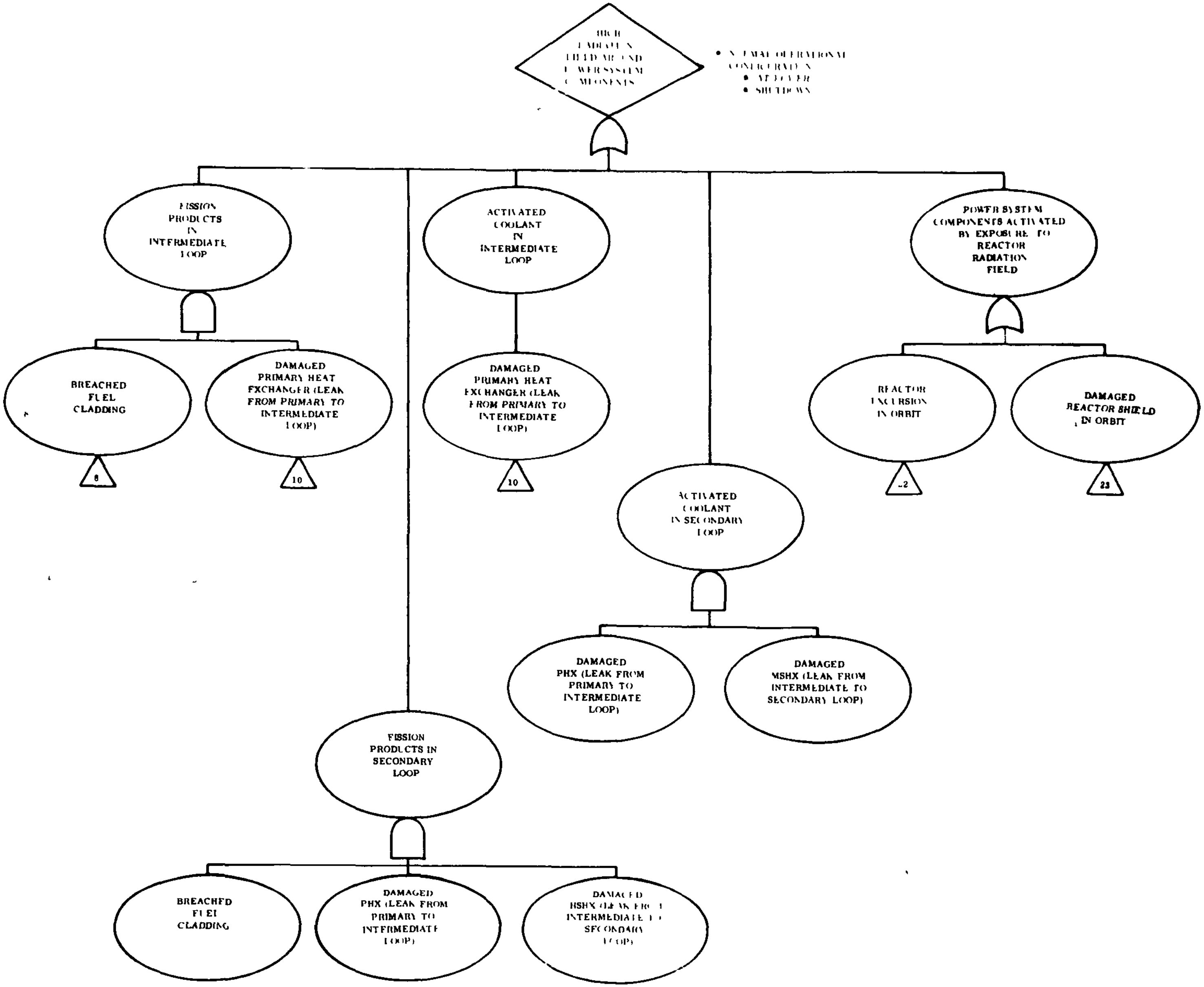


Figure C-5. ZrH Reactor Power Module Fault Tree
(High Radiation Field Around Power System Components)

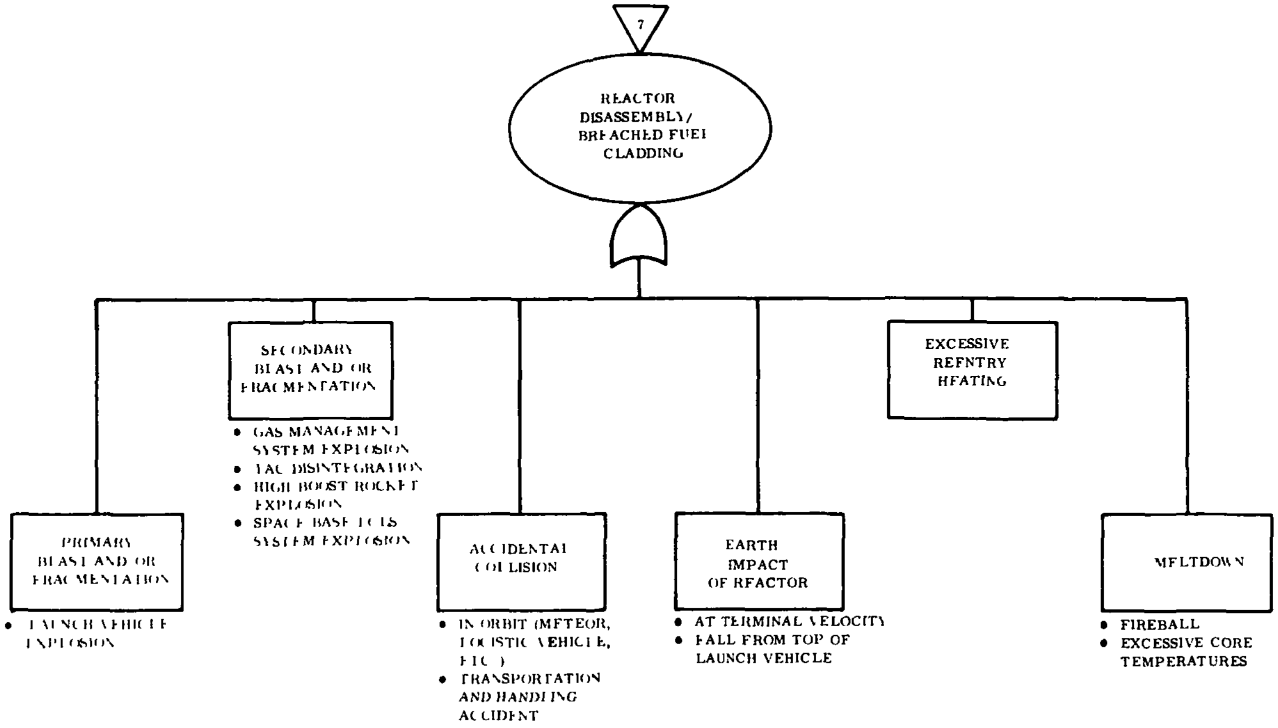


Figure C-6. ZrH Reactor Power Module Fault Tree (Reactor Disassembly/Breached Fuel Cladding)

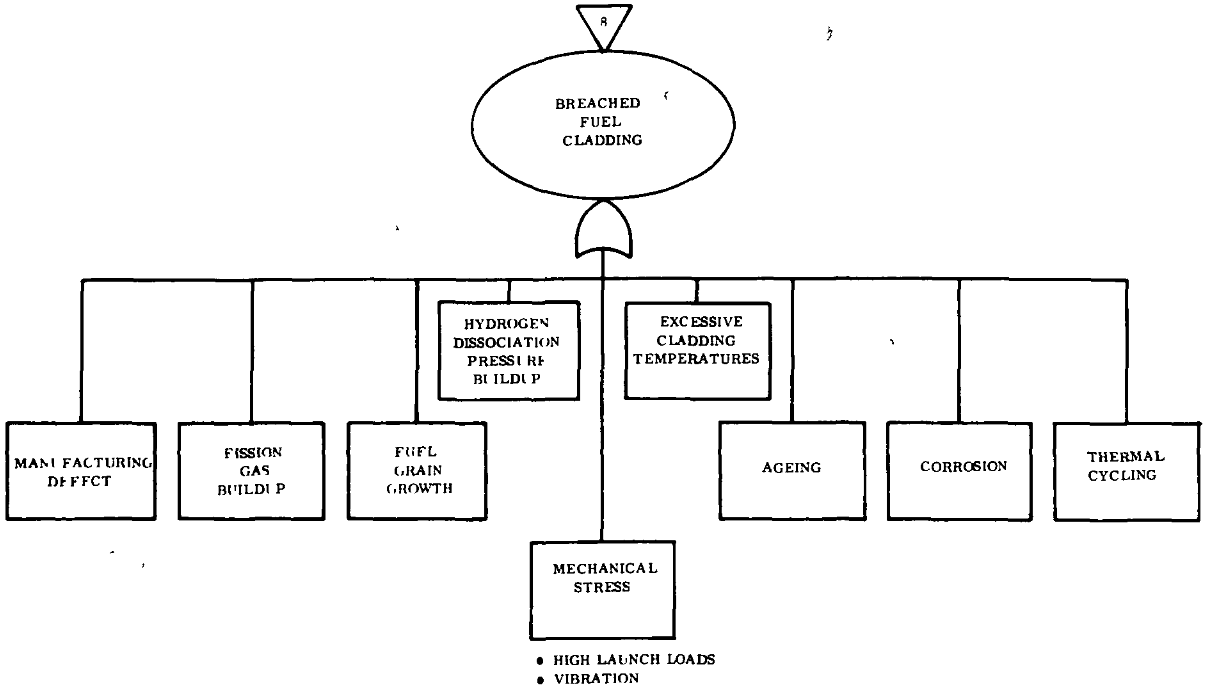


Figure C-7. ZrH Reactor Power Module Fault Tree (Breached Fuel Cladding)

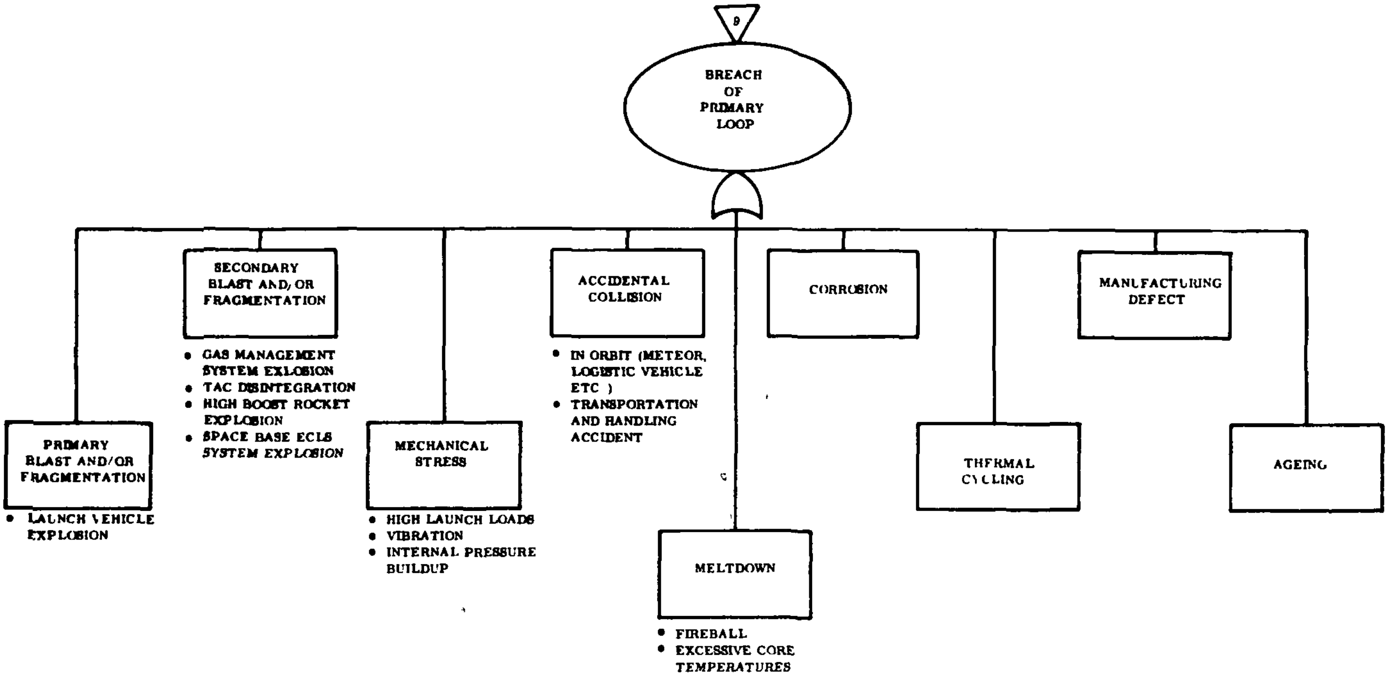


Figure C-8. ZrH Reactor Power Module Fault Tree
(Breach of Primary Loop)

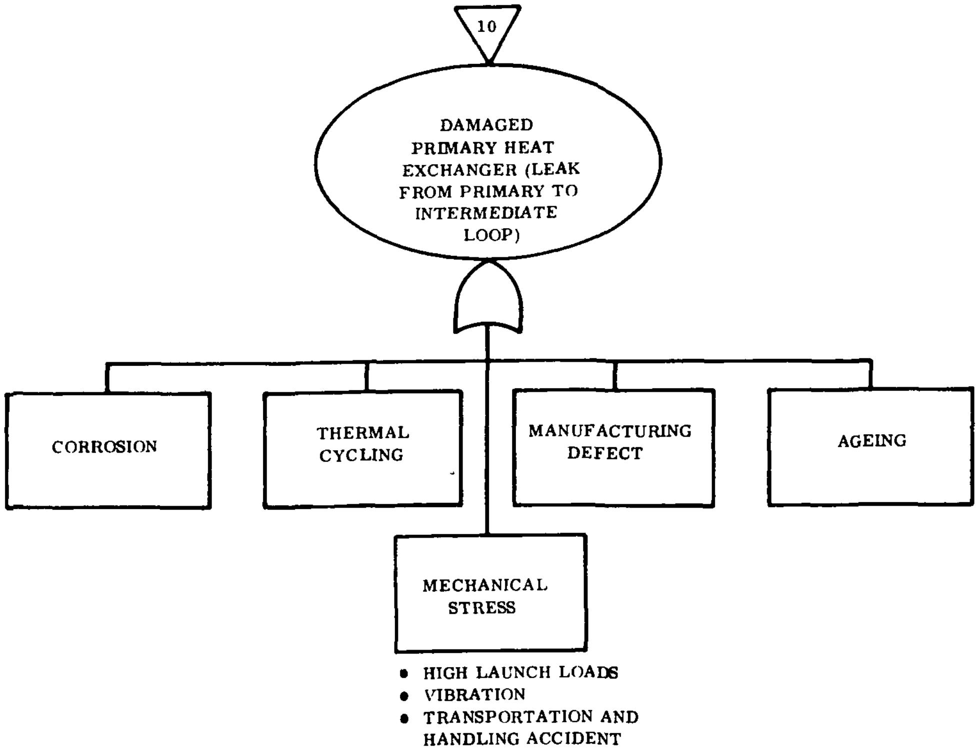


Figure C-9. ZrH Reactor Power Module Fault Tree
(Damaged Primary Heat Exchanger (Leak from Primary to Intermediate Loop))

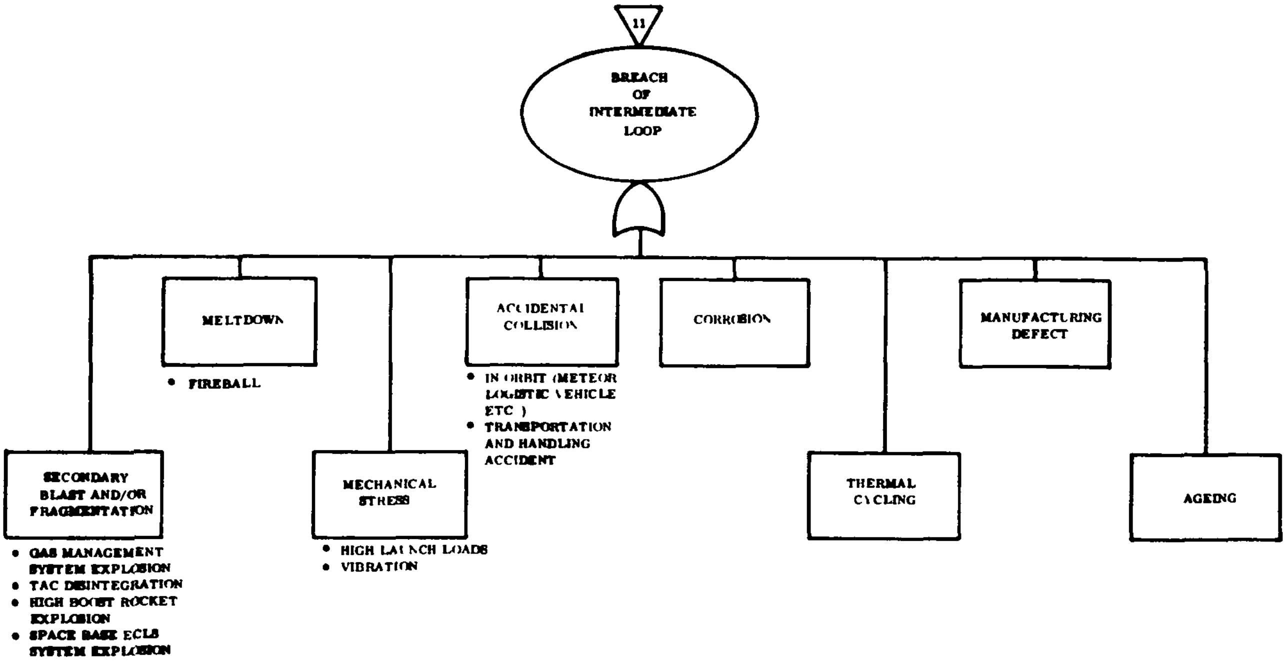


Figure C-10. ZrH Reactor Power Module Fault Tree
(Breach of Intermediate Loop)

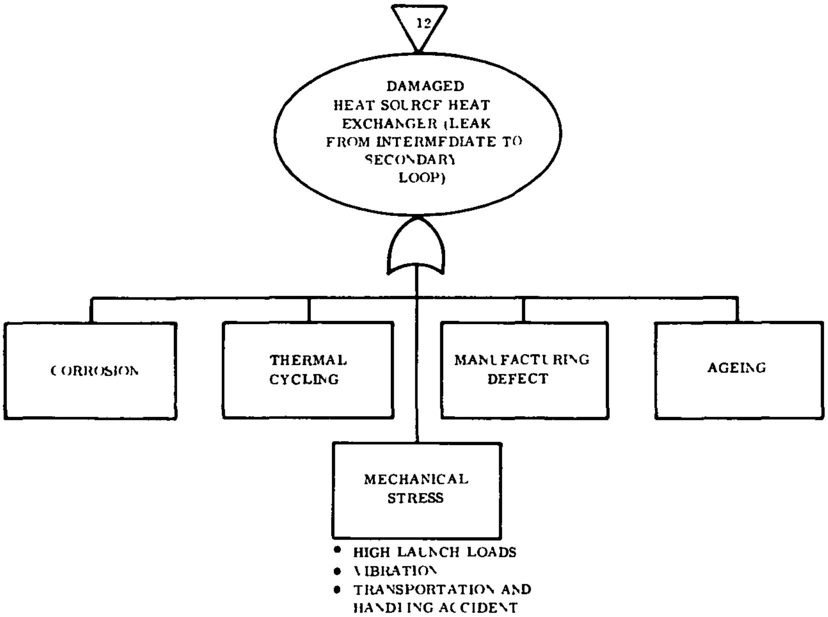


Figure C-11. ZrH Reactor Power Module Fault Tree
(Damaged Heat Source Heat Exchanger (Leak from Intermediate to Secondary Loop))

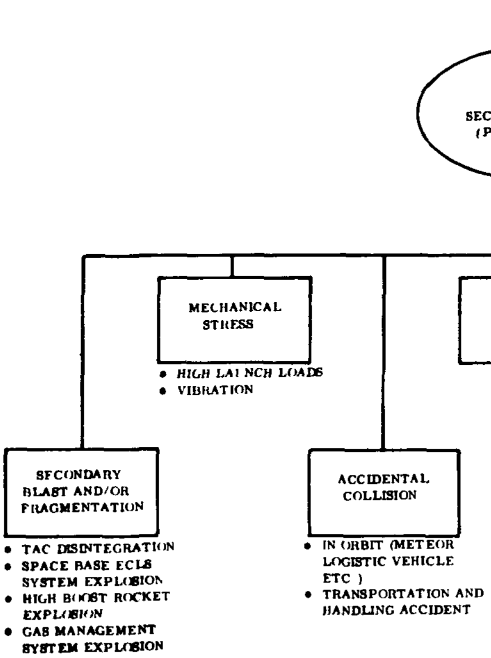


Figure C-12. ZrH Reactor Power Module Fault Tree
(Breach of Secondary Loop)

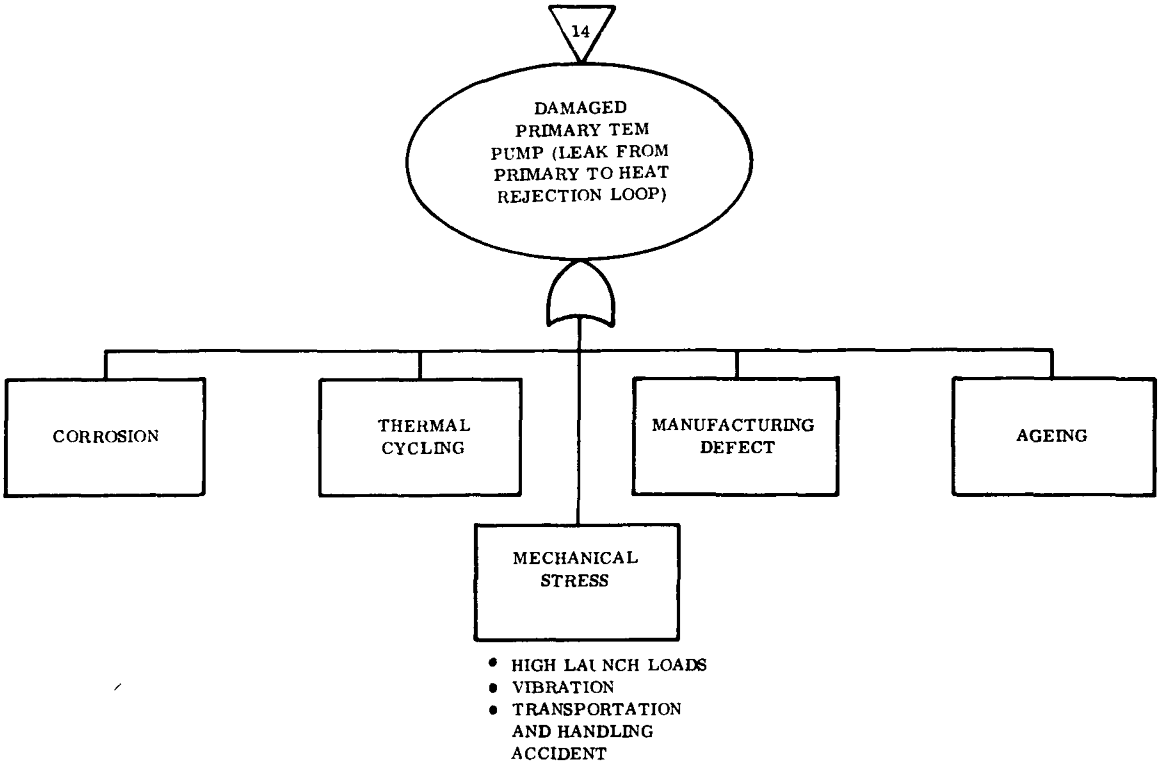


Figure C-13. ZrH Reactor Power Module Fault Tree
(Damaged Primary TEM Pump (Leak from Primary to Heat Rejection Loop))

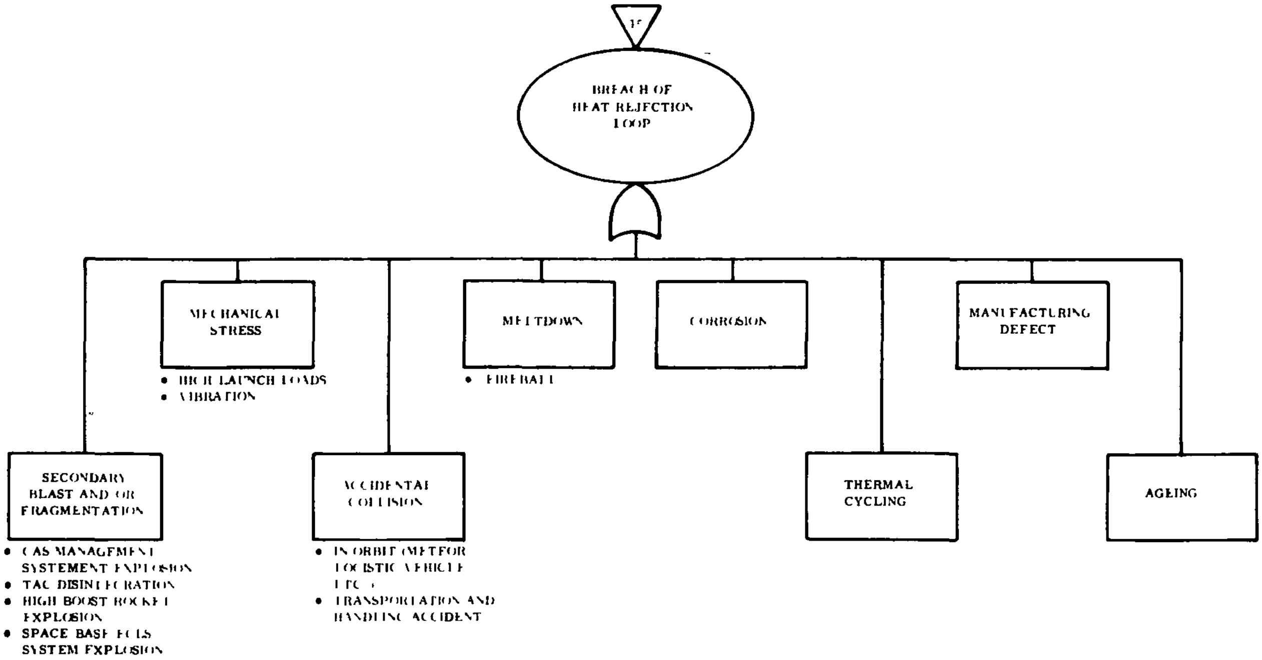


Figure C-14. ZrH Reactor Power Module Fault Tree (Breach of Heat Rejection Loop)

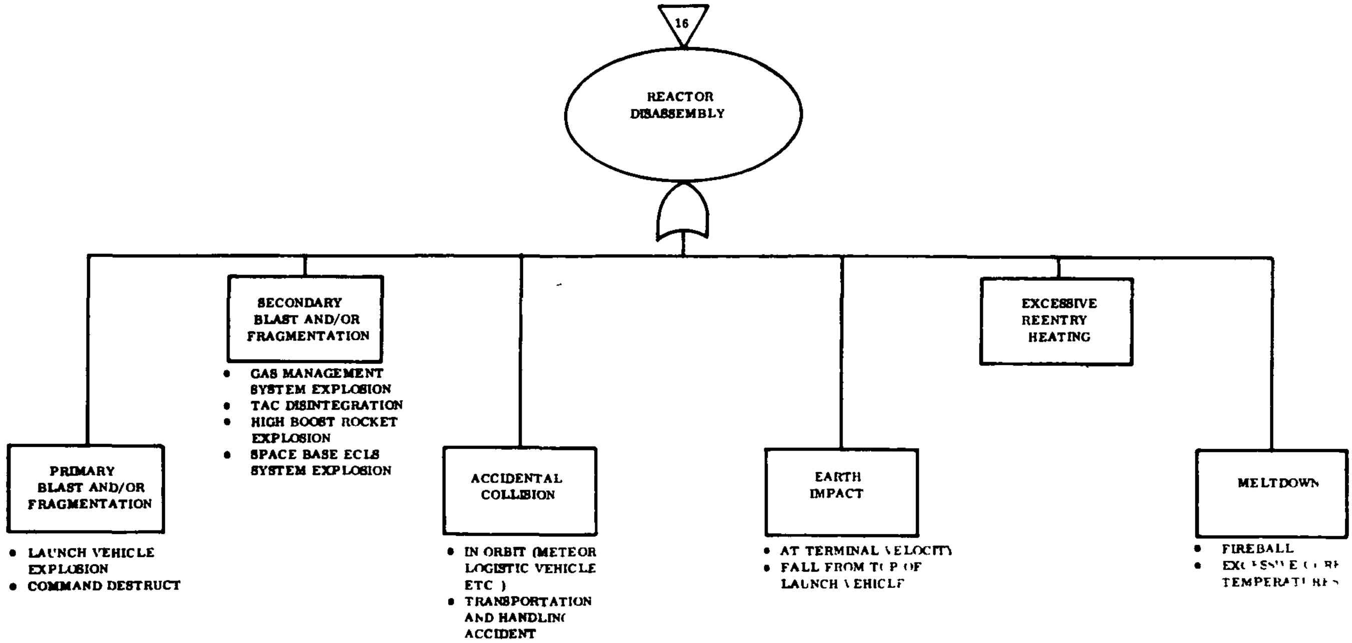


Figure C-15. ZrH Reactor Power Module Fault Tree (Reactor Disassembly)

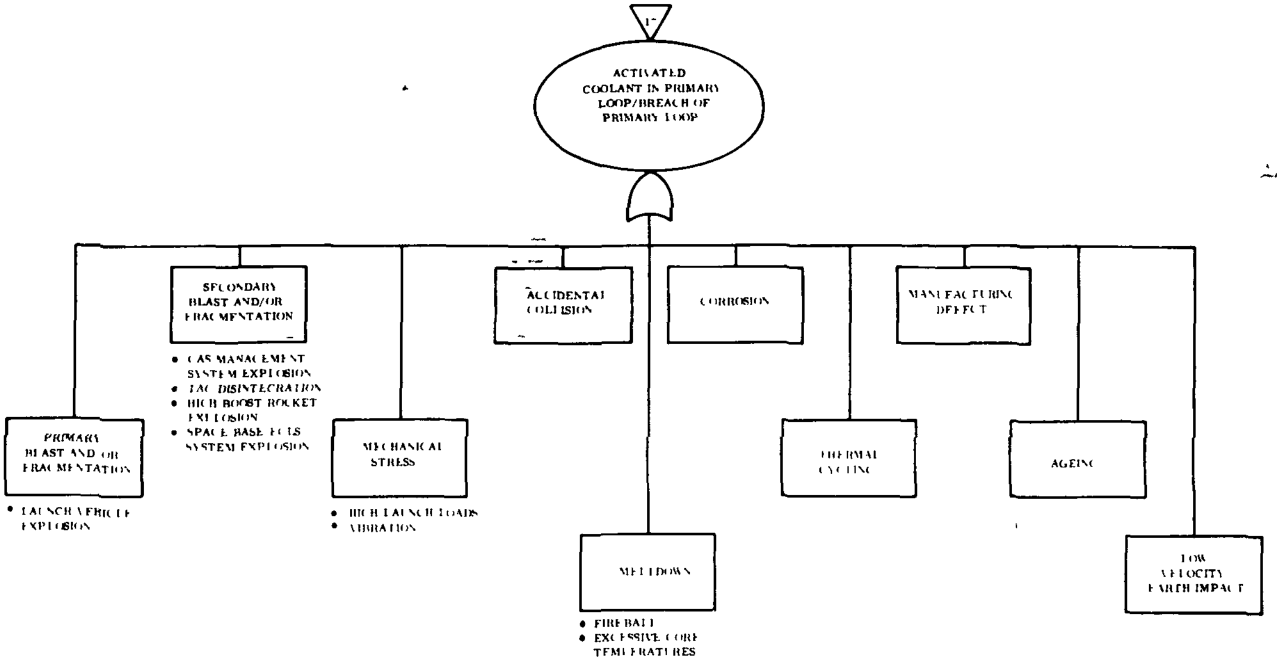


Figure C-16. ZrH Reactor Power Module Fault Tree (Activated Coolant in Primary Loop Breach of Primary Loop)

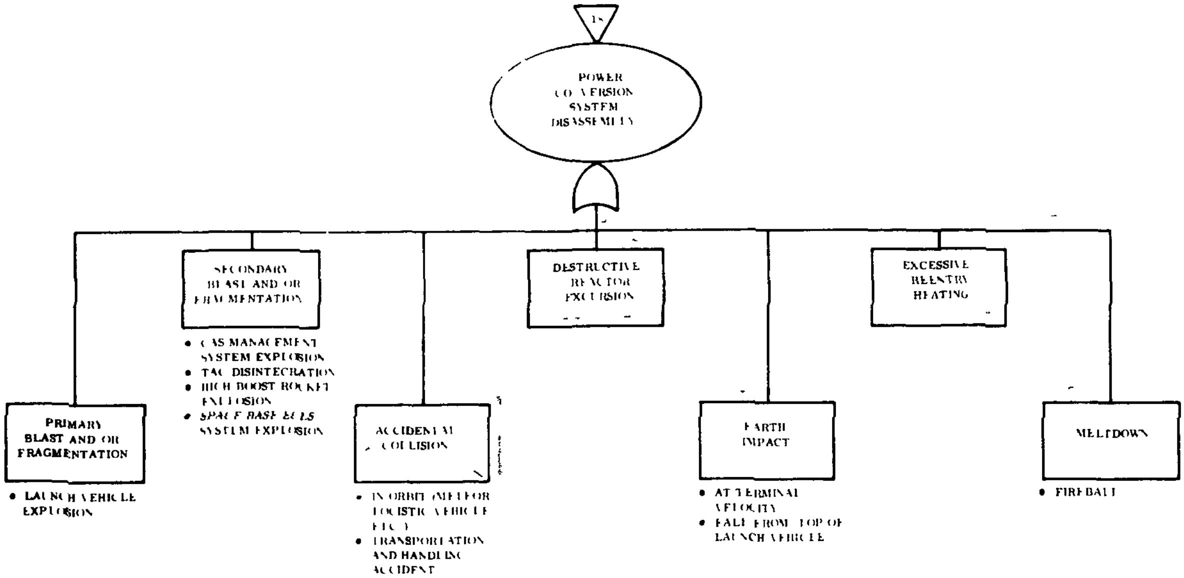


Figure C-17. ZrH Reactor Power Module Fault Tree (Power Conversion System Disassembly)

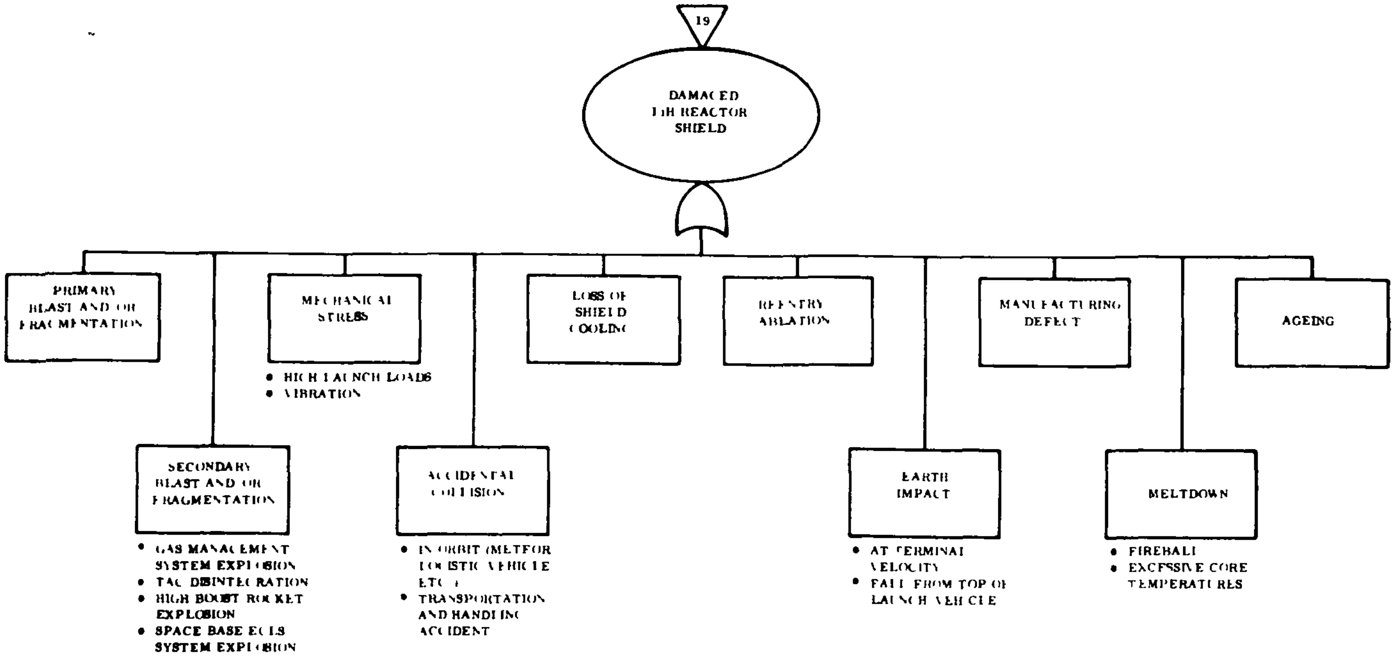


Figure C-18. ZrH Reactor Power Module Fault Tree (Damaged LiH Reactor Shield)

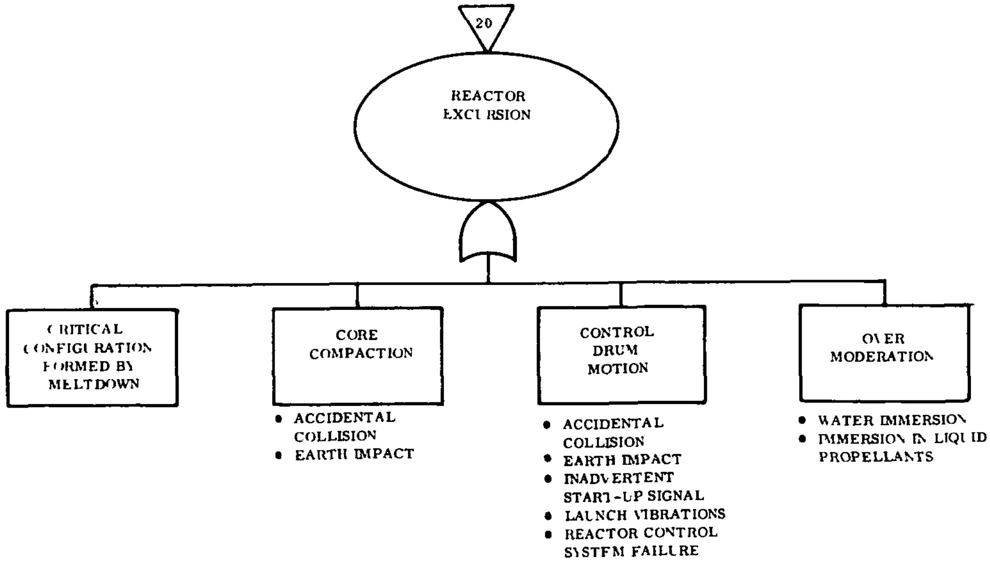


Figure C-19. ZrH Reactor Power Module Fault Tree (Reactor Excursion)

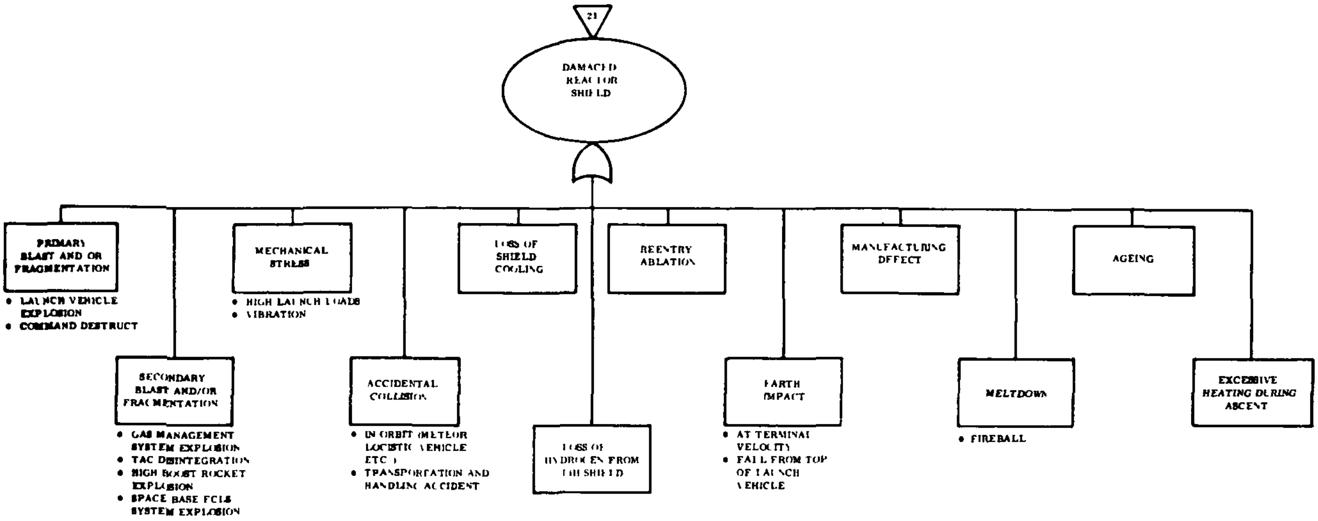


Figure C-20. ZrH Reactor Power Module Fault Tree (Damaged Reactor Shield)

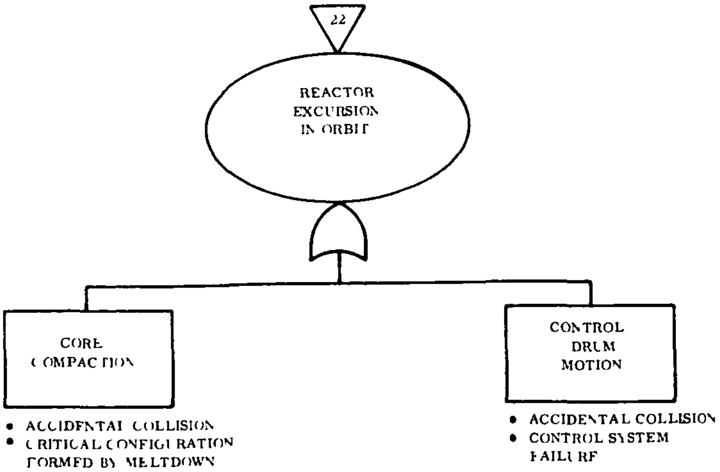


Figure C-21. ZrH Reactor Power Module Fault Tree (Reactor Excursion in Orbit)

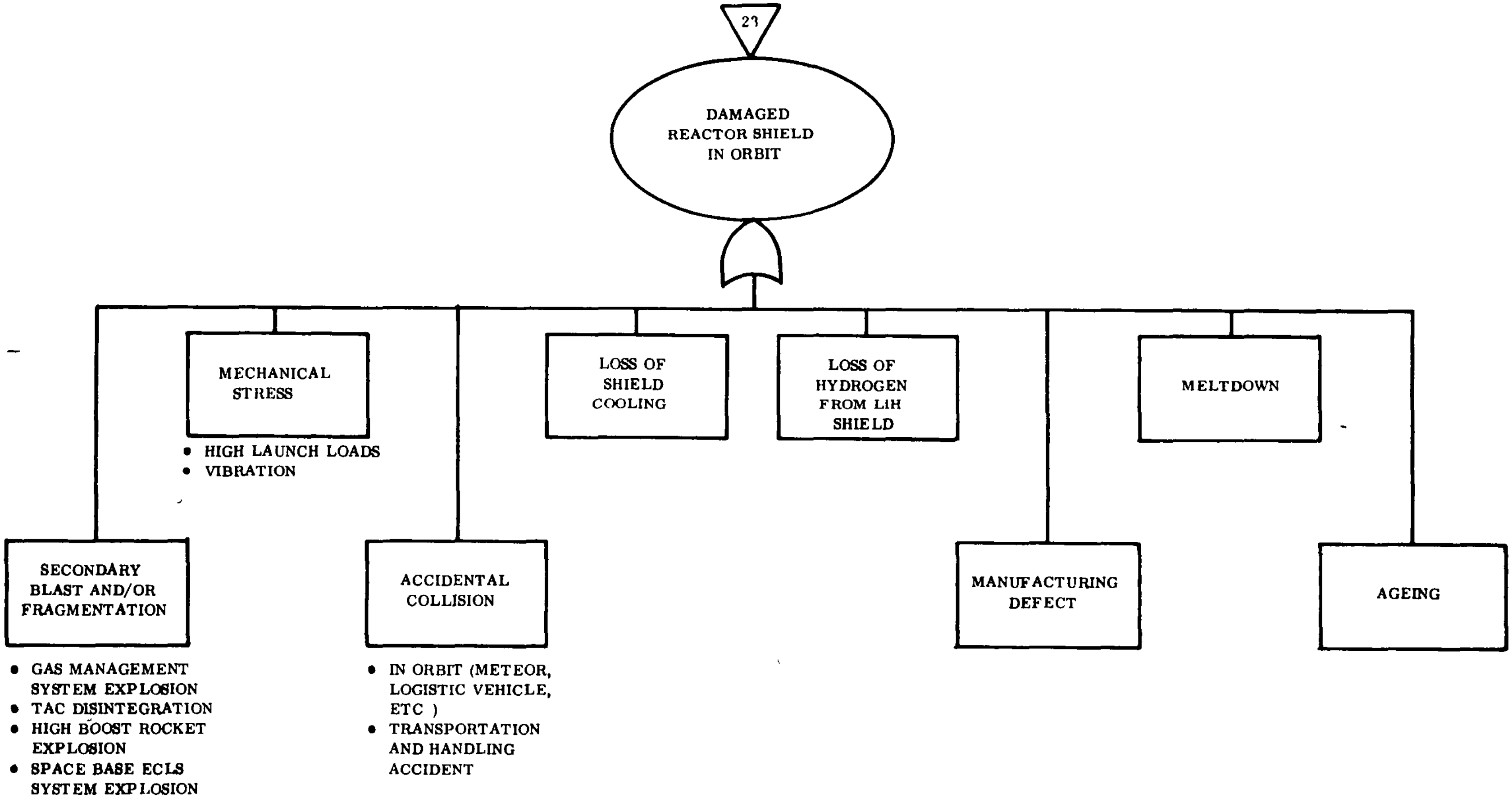


Figure C-22. ZrH Reactor Power Module Fault Tree
(Damaged Reactor Shield in Orbit)

APPENDIX D

REACTOR POWER MODULE (PM) MAINTENANCE AND REPAIR OPERATIONS ANALYSIS

KEY CONTRIBUTORS

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R. J. SPERA

APPENDIX D
REACTOR POWER MODULE (PM) MAINTENANCE AND REPAIR OPERATIONS ANALYSIS

The following sheets were used in identifying hazards associated with Reactor Power Module maintenance and repair.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Reactor Disposal System

• LOCATION	Aft of Engine Room
• ACCESSIBILITY	Internally Accessible - IVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	18-20 mrem/hr at $\sim$10m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
  - Periodic checkout of electronic systems through fault detection and isolation system.

- REPAIR OPERATIONS
  - Replace "black box" electronic equipment and sensors as required by fault detection system.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Reactor radiation levels
  - Normal hazards imposed by IVA operations
  - Remote possibility of disposal engine ignition

- RECOMMENDATIONS
  - A pressurized and temperature controlled engine room of the type used for the Power Module engine room should be considered in future designs.
  - Provisions should be considered for cases where repairs must be effected on the disposal system after it is released from the Space Base.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Auxiliary Heat Rejection Loop/All Coolant Components (Except Radiator)
- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT
  - TEMPERATURE — Space Ambient
  - RADIATION DOSE LEVEL — 39 mrem/hr at 8m from reactor
  - ATMOSPHERE — Space Ambient
- MAINTENANCE OPERATIONS — None

- REPAIR OPERATIONS
  - *Removal and replacement of defective components.*

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - All engine room hazards present during power system operation previously noted.

- RECOMMENDATIONS
  - Mechanical joints in the auxiliary heat rejection loop would facilitate component replacement and lesser time spent in unsafe environment.
  - Power module may be operating or shut down. Auxiliary heat rejection loop is shut down.
  - Location of components in engine room would facilitate repair operations.
  - Repair feasible since cooling fluid is organic.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Heat Rejection Loop/Radiator and Components

• LOCATION	Engine Room (Except Radiator)
• ACCESSIBILITY	Components internally accessible/Main radiator may require EVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr in engine room
ATMOSPHERE	Space Ambient
• MAINTENANCE OPERATIONS	None

- REPAIR OPERATIONS
  - Repair to radiator itself is considered impractical due to NaK hazards and requirement for EVA.
  - Components such as sensors and detectors can be considered repairable provided the repairs do not result in breeching a NaK line.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - Rotating machinery
  - Radiation levels
  - High temperatures

- RECOMMENDATIONS
  - The main radiator should be designed to be redundant.
  - Repair of NaK lines is considered impractical even more so in the case of the radiator since it probably will require EVA.
  - Other components such as sensors and detectors require redundant "fail safe" design philosophy.
  - A modular design should also be considered for ease of replacement where possible.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Brayton Power Conversion Loop/Parasitic Load Resistor

• LOCATION	Engine Room or Radiator Surface
• ACCESSIBILITY	Internally Accessible or EVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient
• MAINTENANCE OPERATIONS	None
• REPAIR OPERATIONS	Replace defective load resistors.

NOTE: The type of parasitic load used on the Space Base Power Module has not been established. For purposes of this study we have assumed passive load resistors that reject their heat by radiating directly to space. It is also assumed they are located on the outside surface of the power module.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Replacement requires EVA operations
  - High voltages may exist
  - Natural and reactor radiation environments

- RECOMMENDATIONS
  - Repair is considered very hazardous. Hazards may be precluded by use of design redundancy and effective circuit design, parallel, series-parallel, etc.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Brayton Power Conversion Loop (BPCL)

- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT

TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS — None

- REPAIR OPERATIONS
  - Repair of gas containment wall fracture or puncture by patch welding.
  - Replacement of component by cutting and rewelding a gas containment duct.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - All engine room hazards present during power module operation

- RECOMMENDATIONS
  - Repair to gas lines in BPCL is considered practical. Use of standby piping loops may be feasible through redundant design of appropriate valve and piping configurations.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Brayton Power Conversion Loop/Control System Components
- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT

TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
  - Periodic check of operation of modular electronic and electrical components in standby BPCL's.
- REPAIR OPERATIONS
  - Replace defective modular components
- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - All engine room hazards present during power module operation previously noted.
  - Possible electrical hazard
- RECOMMENDATIONS
  - Power Module may be operating or shut down. BPCL is shut down.
  - Provide modular "black box" design approach to facilitate replacement.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - BPCL-Instrumentation Sensors

• LOCATION	Engine Room
• ACCESSIBILITY	Internally Accessible - IVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
  - Periodic check of instrumentation sensor operation.

- REPAIR OPERATIONS
  - Replacement of defective sensor(s)

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - All engine room hazards present during power module operation previously noted.

- RECOMMENDATIONS
  - Power Module may be operating or shut down. BCPL is shut down.
  - Where possible, sensor design and location should preclude requirement for breach of BCPL gas containment.
  - Provide "fail safe" redundant sensors.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - BPCL/Turbine Bypass and/or Shutoff Valve

- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT
  - TEMPERATURE — Space Ambient
  - RADIATION DOSE LEVEL — 39 mrem/hr at 8m from reactor
  - ATMOSPHERE — Space Ambient

- MAINTENANCE OPERATIONS
  - Periodic check of mechanical operation of valve(s)

- REPAIR OPERATIONS
  - Replace valve actuator(s)
  - Replace entire valve

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Proximity of NaK coolant
  - All engine room hazards present during Power Module operation previously noted.

- RECOMMENDATIONS
  - Power Module may be operating or shut down. BPCL is shut down.
  - Actuator should be designed so that its removal and replacement does not breach BPCL gas containment.
  - Design repair requirements into valves which reduce complexity and time required for replacement operations.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Brayton Power Conversion Loop/Gas Management System

• LOCATION	Engine Room
• ACCESSIBILITY	Internally Accessible - IVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
    - Resupply of working gas reservoir may be required depending on system leak rates and number of start-ups.
    - Periodic start-up of standby units may necessitate gas replacement by Shuttle resupply.
- REPAIR OPERATIONS
    - Repair gas line leaks
    - Replace components, pressure regulators, sensors and detectors
- UNSAFE CONDITIONS/POTENTIAL HAZARDS
    - Proximity of NaK coolant lines and rotating equipment
    - High gas pressures
    - Relatively high temperatures
- RECOMMENDATIONS
    - Provide design redundancy such that gas management systems for all PCS's are equipped with common valving and piping systems.
    - Sensors and detectors should be designed with redundant philosophy. System components should be designed on modular basis for easy replacement.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Brayton Power Conversion Loop/Brayton Rotating Unit (BRU)

- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT

TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
  - The standby BRU's should be designed to allow for periodic operational checkouts.

- REPAIR OPERATIONS
  - Replace entire BRU assembly

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Corrosive NaK coolant
  - Possible presence of fission products/activated coolant
  - Possible NaK fire
  - All engine room hazards, etc.

- RECOMMENDATIONS
  - Power module may be operating or shut down. BRU is shut down.
  - Heat exchanger designs in BPCL that allowed BRU replacement without cutting or disconnecting NaK lines would greatly increase safety of replacement operation.
  - Mechanical assist devices would be required for controlled physical handling of complete BRU assembly.
  - The BRU should be designed as a modular package such that it can be disconnected from the heat rejection loop and intermediate loops without having to cut into NaK lines. Gas line interfaces with low helium leak rates are preferred over systems requiring welds.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Reactor Intermediate Loop/Isolation Valve

- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT

TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS — None

- REPAIR OPERATIONS
  - Maintenance repair of valve actuator
  - Cut out complete valve and weld new one in place.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - NaK toxicity
  - Possibility of NaK activation (radioactivity)
  - Possibility of NaK fire
  - High temperature levels

- RECOMMENDATIONS
  - Repair of NaK lines considered impractical in zero "g" environment.
  - Redundant NaK lines should be considered for all NaK loops.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Reactor Intermediate Loop/EM Pump and Accumulator

- LOCATION — Engine Room
- ACCESSIBILITY — Internally Accessible - IVA
- ENVIRONMENT

TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS — None

- REPAIR OPERATIONS
  - Cut out defective pump and/or accumulator and weld new unit in place.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - NaK toxicity
  - Possibility of radioactive coolant
  - Possibility of NaK fire
  - Possibility of radiation dose from fission products

- RECOMMENDATIONS
  - Repair of NaK pumps is considered impractical if it requires cutting into a NaK piping system. Repair of the electrical portions of the pump may be feasible.
  - Past experience (SNAP-10A) in the use of accumulators indicates the bellow type to have a relatively high failure rate.
  - Design redundancy is highly recommended for NaK pumps and accumulators.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Reactor Disposal System

• LOCATION	Engine Room
• ACCESSIBILITY	Internally Accessible - IVA
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	39 mrem/hr at 8m from reactor
ATMOSPHERE	Space Ambient

- MAINTENANCE OPERATIONS
  - Periodic check of operation of modular electronic components

- REPAIR OPERATIONS
  - Replacement of defective modular component

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - Possible electrical hazard
  - Proximity to reactor intermediate NaK loop
  - Possible high radiation levels due to fission products/activated coolant in intermediate loop
  - Rotating machinery
  - Localized high temperature levels

- RECOMMENDATIONS
  - Modularized black boxes should be designed for easy, rapid disconnect and plug in.
  - Design "fail safe" control system.

PM MAINTENANCE AND REPAIR OPERATIONS

NUCLEAR SAFETY ASPECTS

- SUBSYSTEM/COMPONENT - Reactor Primary Loop

• LOCATION	Gallery
• ACCESSIBILITY	EVA Only
• ENVIRONMENT	
TEMPERATURE	Space Ambient
RADIATION DOSE LEVEL	600 mrem/hr at 1.8 m from reactor
ATMOSPHERE	Space Ambient
• MAINTENANCE OPERATIONS	None
• REPAIR OPERATIONS	None considered practical.

- UNSAFE CONDITIONS/POTENTIAL HAZARDS
  - High radiation dose levels (200 rem/hr 24 hours after shutdown).
  - Corrosive NaK coolant
  - All EVA hazards
  - High temperatures

- RECOMMENDATIONS
  - Repair to primary loop is considered highly impractical due to the severity of the potential hazards. Design redundancy is strongly recommended.

APPENDIX E

CALCULATIONS FOR SPACE BASE REENTRY SYSTEMS

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APPENDIX E
CALCULATIONS FOR SPACE BASE REENTRY SYSTEMS

E.1 GENERAL

Analysis of disposal techniques for the Space Base Power Modules requires a series of orbital mechanics calculations to determine long life orbit requirements and to assess the consequences of system malfunction during the disposal maneuver. This Appendix provides the results of calculations that were conducted.

Basically, the calculations are organized into the following tasks:

1. Disposal Propulsion Requirements
2. Orbit Lifetime
3. Reentry Characteristics

Design information used for this analysis is listed below:

1. Free molecular ballistic coefficient (W/C_DA) of Power Module is 1905 Newton/m^2 (39.8 lb/ft^2)
2. Free molecular ballistic coefficient (W/C_DA) of Reactor/Shield configuration is 16,853 Newtons/m^2 (352 lb/ft^2)
3. Reference orbit has a 500 km (273 nm) altitude inclined at 55°

E.2 ANALYSIS

E.2.1 DISPOSAL PROPULSION REQUIREMENTS

Assuming that the Power Module (PM) has been successfully separated from the Space Base and positioned for transfer to a high disposal orbit, propulsion requirements have been identified for transfers from the reference orbit to various disposal orbits. The transfer consists of two propulsive maneuvers - a thrust at the reference orbit which results in transfer

to the disposal altitude, and a thrust at apogee to effect circularization at the disposal altitude. Figure E-1 displays (1) ΔV required to transfer (ΔV_t), (2) ΔV required to circularize (ΔV_c), and (3) total ΔV as a function of final circular disposal orbit. Since the indicated ΔV is assumed to occur instantaneously, it is independent of the mass to be transferred and the means by which the propulsive maneuvers are accomplished. For purposes of comparison, Figure E-1 shows that to reach a circular disposal orbit of 1290 km (700 nm) a ΔV of 400 m/sec (1315 ft/sec) is required; whereas, it has been calculated that to achieve Earth escape requires 3140 m/sec (10,300 ft/sec.)

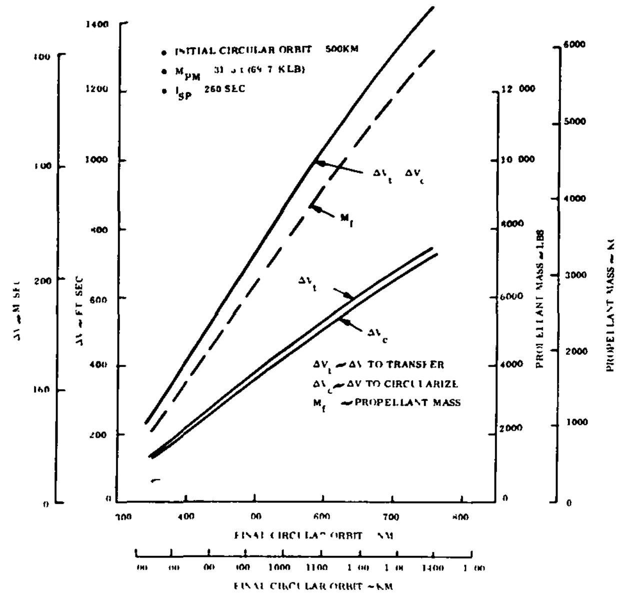


Figure E-1. Propulsion Requirements for Transfer from 500 km (273 km) Circular Orbit

Also, the amount of propellant necessary to boost the PM from the reference orbit to a higher disposal orbit is presented in Figure E-1. Propellant mass is given by the expression,

$$\frac{M_f + M_{PM}}{M_{PM}} = e^{\Delta V/g\, Isp}$$

where:

M_f = Propellant mass

M_{PM} = Mass of Power Module

ΔV = Total ΔV required to perform maneuver

g = Gravitational acceleration

I_{sp} = Rocket engine specific impulse

The propellant mass shown in Figure E-1 was based on a rocket engine specific impulse of 260 sec., which is characteristic of solid propellants. The propellant mass required to achieve Earth escape of the PM is 76t (168.5 klb) of solid propellant or 35t (78.2 klb) of liquid propellant with a characteristic specific impulse of 425 sec.

E.2.2 ORBIT LIFETIME

This task provides a calculation of lifetime of those orbits in which the PM or Reactor/Shield configuration may be placed during the disposal maneuver. The calculational procedure is discussed in Reference 1.

It should be noted that this method of predicting orbit lifetime results in significantly higher lifetimes than those predicted by the TRW Space Handbook and some unauthenticated curves appearing in various technical documents. Without attempting to resolve entirely this apparent conflict, a possible cause for the discrepancy will be proposed. For orbits of 275 km (150 nm) or greater the eleven-year cyclic function of solar flux intensity has a significant influence on orbit lifetime. The effect of solar flux on atmospheric density, hence orbit lifetime, can be described by the parameter,

$$S = 25 + 0.8\,\bar{F}_{10.7} + 0.4\,(F_{10.7} - \bar{F}_{10.7}) + 10\,K_p$$

where $F_{10.7}$ is the daily value of the 10.7 cm. solar flux, $\bar{F}_{10.7}$ is its yearly average, and K_p is the geomagnetic index (having a range of 0-9). The parameter, S, is directly proportional to atmospheric density and inversely proportional to orbit lifetime. Figure E-2 displays the observed value of S for 1958 to 1966 and supplies a predicted value of S along with corresponding 2σ limits from the nominal for the period 1966 to 1974. The horizontal line shown on Figure E-2 represents the value of S assumed in the 1959 ARDC atmospheric model. Consequently, if an orbit lifetime calculation is based on the 1959 ARDC atmospheric density model, the assumed solar flux and density are significantly greater than the average values observed over a complete solar flux cycle. The predicted orbit lifetime would, therefore, be significantly less than that predicted by a model that assumes a time-varying atmosphere.

The procedure selected for this analysis is provided in Reference 1 and is summarized by the expression,

$$\text{lifetime (days)} = L_1 \times \frac{M}{C_D A} \times f_{iw} \times f_d$$

where L is a factor obtained as a function of apogee and perigee altitude, $M/C_D A$ is ballistic coefficient in kg/m^2, f_{iw} is a correction factor given as a function of initial inclination and argument of perigee, and f_d is the solar flux correction factor as a function of inclusive calendar dates that the satellite remains in orbit and initial perigee altitude. The factors, L_1, f_{iw}, and f_d can be obtained from Reference 1. Since f_d cannot be predicted exactly because of the uncertainty with which S is predicted as shown in Figure E-2, curves of 2σ upper and lower limits of f_d have been generated in Reference 1.

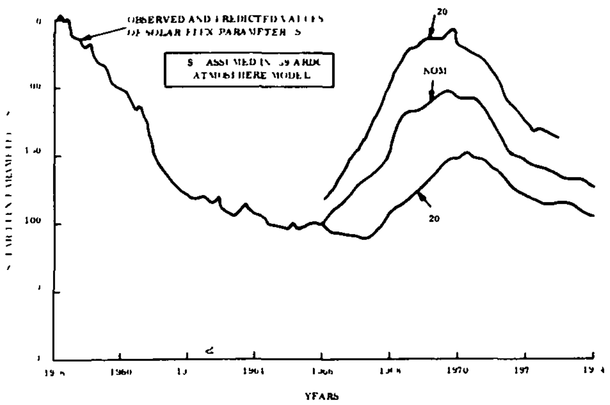


Figure E-2. Solar Flux as a Function of Time

Orbit lifetimes were subsequently calculated for the range of orbits that are most likely to be attained as a result of a disposal maneuver. Figure E-3 presents the orbit lifetime/ballistic coefficient ratio for circular orbits as a function of altitude and for elliptical orbits as a function of apogee altitude with perigee altitude of 500 km. Elliptical orbits result if the transfer impulse is accomplished at the reference orbit, but the impulse which is applied at apogee to effect circularization fails. The band in Figure E-3 was constructed

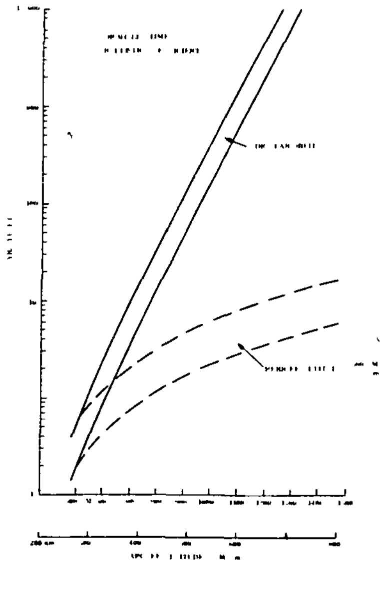


Figure E-3. 2-Sigma Limits on Orbital Lifetime for Orbit of 500 km (273 nm) Perigee

as the 2σ upper and lower limits on predicted lifetime. The 2σ lower bound on predicted orbit lifetime is presented in Figure E-4 for the PM and Reactor/Shield configuration in circular and elliptical orbits.

E.2.3 REENTRY CHARACTERISTICS

Modifications were made to the existing Transorbit Trajectory computer code in order that entry conditions at 122 km (400,000 ft) could be determined as a result of specified burnout characteristics at high altitude. The purpose of this task is to estimate the velocity and flight path angle of the PM at 122 km assuming a guidance malfunction along with complete propellant depletion by the disposal engine. A map of entry velocity and flight path angle was constructed by varying the thrust vector from 0^{o} to -180^{o} from the horizontal.

For the case of disposal engine misfire at the reference orbit, Figure E-5 presents the map of entry conditions. The indicated ΔV's of 130, 225, and 400 m/sec (425, 740, and 1315 ft/sec) represent the total ΔV necessary to achieve circular disposal altitudes of 735, 920, 1290 km (400, 500, and 700 nm), respectively.

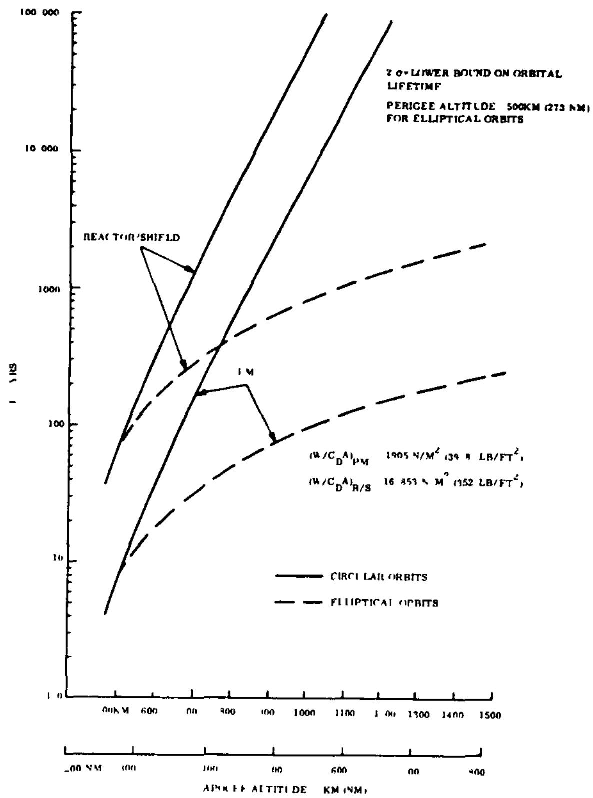
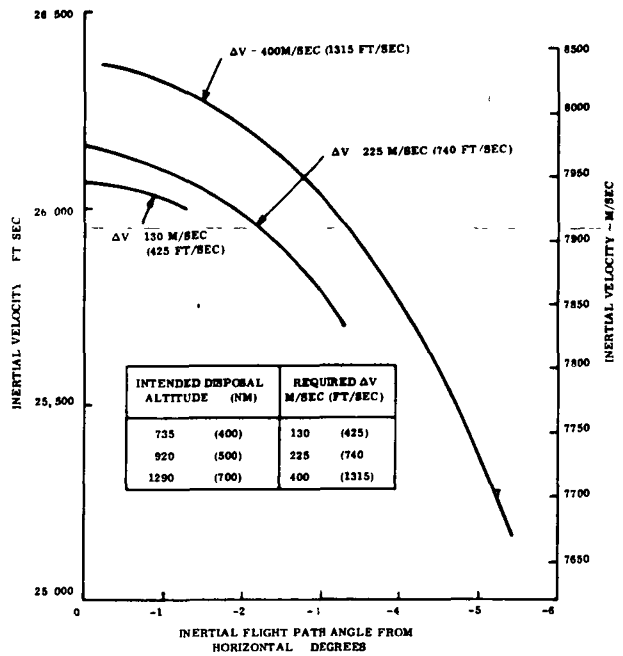


Figure E-4. Orbital Lifetime of Power Module and Reactor/Shield Combination



INTENDED DISPOSAL ALTITUDE (NM)		REQUIRED ΔV M/SEC (FT/SEC)	
735	(400)	130	(425)
920	(500)	225	(740
1290	(700)	400	(1315)

Figure E-5. Entry Conditions at 400,000 Feet Resulting from Disposal Engine Misfire at 273 nm Circular Orbit

The second case considered is that in which successful transfer of the PM from reference orbit to the disposal altitude is accomplished, but the instantaneous thrust to effect circularization at the disposal altitude fires at the improper angle. If the ΔV to circularize is fired at any angle from a 735, 920, or 1290 km apogee, direct entry to 122 km will not occur. The decrement in energy caused by engine misfire does not provide sufficient energy for the elliptical orbit to degrade to an orbit which penetrates the atmosphere. Consequently, such a high altitude misfire will result eventually in an Earth orbit decay type reentry.

E.2.4 SUMMARY

The preceding calculations were intended as a basis for additional disposal maneuver and reentry analysis. The propulsion requirements for placing the PM and Reactor/Shield configuration into a disposal orbit and subsequently determining the reentry conditions as a result of engine misfire form the basis for the reentry analysis portion of disposal maneuver safety considerations.

In addition, estimating orbit lifetimes for those orbits that may be achieved during the disposal maneuver is fundamental to selecting a desirable disposal orbit and sequence of disposal operations.

REFERENCES

1. Richards, T.J., "A Graphical Method for Predicting Satellite Lifetime Based on a Time-Varying Atmospheric Density Model", MSFC Contract NAS8-11121, 1966.

CONVERSION FACTORS
INTERNATIONAL TO ENGLISH UNITS

Physical Quantity	International Units	English Units	Conversion Factor Multiply By
Acceleration	m/sec^2	ft/sec^2	3.281
Area	m^2	ft^2	10.764
		in^2	1550.39
Density	Kg/m^2	lb/ft^3	6.242×10^{-2}
		lb/in^3	3.610×10^{-5}
Energy	Joule	Btu	9.479×10^{-4}
Force	Newton	lbf	2.248×10^{-1}
Length	m	ft	3.281
		nm	5.399×10^{-4}
Mass	Kg	lbm	2.205
Power	watt	Btu/sec	9.488×10^{-4}
		Btu/min	5.691×10^{-2}
		Btu/hr	3.413
Pressure	$Newton/m^2$	Atmosphere	3.413
		lbf/in^2	1.451×10^{-4}
		lbf/ft^2	2.088×10^{-2}
Speed	m/sec	ft/sec (fps)	3.281
Temperature	K	F	$(9/5 - 459.67/t_K)$
Volume	m^3	in^3	6.097×10^4
		ft^3	35.335

GLOSSARY OF TERMS

Abort	Premature and abrupt termination of an event or mission because of existing or imminent degradation or failure of hardware (In the safety analysis, no distinction is made between an accident and abort.)
Accident	An undesirable unplanned event which may or may not result from a system failure or malfunction.
Airborne Material	Radioactive gases, vapors and particulates released to the air
Breached	Fuel elements, coolant loops, pressure vessel, core, or radiation shield are (a) physically torn by thermal or mechanical stresses, (b) cut open by fragmentation or (c) split open by internal pressures.
Bulk Damage (Radiation)	Radiation causing atomic displacement in semiconductor devices - sometimes commonly referred to as "crystal" damage
Contamination	A condition where a radioactive material is mixed or adheres to a desirable substance or where radioactivity has spread to places where it may harm persons, experiments or make areas unsafe
Control Drum Motion	Rotation of the control drums or drum toward or away from the most reactive position within a reactor (As used in safety analysis results in a reactor excursion)
Core Compaction	The act of increasing the density of the core which results in increased reactivity and possible criticality
Cover Gas	A gas blanket used to provide an inert atmospheric environment around hardware to minimize potential reactions which can give rise to accident situations
Credible	An event having a relative or cumulative probability of occurence of $> 10^{-12}$
Criticality	The act of obtaining and sustaining a chain reaction
Critical Mass	The mass of fissionable material necessary to obtain criticality
Cumulative Probability	Sometimes referred to as "Mission probability" is the overall probability of a sequence of events occurring (product of 'relative probabilities" of the individual events along a path of an abort sequence tree)
Damaged	Same as "Breached"
Decontamination	The removal of undesired dispersed radioactive substances from material, personnel, rooms, equipment, air, etc (e g , washing, filtering, chipping)
Destructive Excursion	An excursion (safety analysis assumes $\sim$ 100 MW-sec) accompanied by a complete disassembly of the reactor, a prompt radiation emission and release of fission product gases, vapors and particulates
Disassembly/Disassembled	Nuclear hardware (e g , reactor) which has been violently broken or separated into parts and not capable of forming a critical mass
Disposal	The planned discarding or recovery of nuclear hardware
Distributed Material	The spread of nuclear fuel and radioactive debris on the earth's surface following impact or destructive excursion
Dose Guidelines	Established radiation levels used in the nuclear safety analysis for evaluating number of exposures and in determining operating limits and boundaries
Dosimetry	Techniques used in the measurement of radiation

GLOSSARY OF TERMS (CONT)

Dynamic Interference	An experiment radiation effect where the flux rate above some threshold (a fraction of the experiment signal-to-noise ratio at maximum sensitivity, for electronic detectors) causes noticeable degradation of data quality
Early Reactor Disposal	Attempted disposal of the reactor prior to its successful completion of 5 years operational lifetime
Electrical Power System	All components (heat source, regulation, control, power conversion and radiators) necessary for the development of electrical power The reactor electrical power system includes all hardware associated with the Power Module with the exception of the Disposal System.
End of Mission	Generally associated with the termination of the mission or flight Is also used to define those activities involved with disposal and recovery of hardware after intended lifetime
Excursion	A rapid and usually unplanned increase in thermal power associated with the operation of a power reactor
Exposure Limit	Total accumulated or time dependent radiation exposure limits imposed on personnel by regulatory agencies or limits which preclude equipment damage
Fission Products	The nuclides (quite often radioactive) produced by the fission of a heavy element nuclide such as U-235 or Pu-239
Fuel	Fissionable material in a reactor or radioisotopes in a heat source used in producing energy
Fuel Element/Capsule	A shaped body of nuclear fuel prepared for use in a reactor or heat source Common usage involves some form of encapsulation
Fuel Element Ablation	Fuel element clad and/or fuel removed by reentry heating, releasing fission products to the atmosphere
Fuel Element Burial	Individual fuel elements beneath the ground surface completely covered by soil
Gallery	The compartment of the reactor shield which houses the major primary loop components
Ground Deposited Particles	Particles deposited on the ground from radioactive fallout
Hazard	An existing situation caused by an unsafe act or condition which can result in harm or damage to personnel and equipment
Hazard Source	The location and/or origin of the hazard
Immediate Reentry	Very early reentry of the reactor (e g , misaligned thrust vector which causes firing of the reactor disposal rockets toward earth resulting in 1-2 day reentry)
Impact in Deep Ocean	Reentering and/or impact of nuclear material in the ocean, beyond the Continental Shelf where contamination of the food chain is extremely remote
Impact in Reservoir	Reentering and/or impact of nuclear material in reservoir containing potable drinking water
Impact in Water Containing Edible Marine Life	Reentering and/or impact of nuclear material on the Continental Shelf or in a body of water such as a lake, river or stream where contamination of the food chain is likely.
Intact Reentry/Reactor	A nuclear system that retains its integrity upon impact and in the case of a reactor is capable of undergoing an excursion.
Integrated/Cumulative Dose	The total dose resulting from all or repeated exposures to radiation
Interfacing Vehicle	Any defined module, spacecraft, booster or logistic vehicle which may have an interaction with the Manned Space Base.

GLOSSARY OF TERMS (CONT)

Ionization Damage	Radiation causing surface damage in materials (e g., the fogging of film).
Land Impact	Nuclear hardware which impacts land at terminal velocities following reentry and lower velocities during prelaunch or early in the launch/ascent phase.
Loss of Coolant	Loss of organic or liquid metal coolant in reactor coolant loops due to failure/accident
Mission Support	Supporting functions provided the Space Base Program by ground personnel and interfacing vehicles throughout all mission phases.
Moderator	Material used in a nuclear reactor to slow down neutrons from the high energies at which they are released to increase the probability of neutron capture Water and hydrogen are moderators in a thermal reactor
NaK-78	An alloy of sodium (22% by weight) and potassium (78%) used as a liquid metal heat transfer fluid
No Discernible Hazard	Represents no hazard to the general populace
Non-credible	An event having a relative or cumulative probability of occurrence of $< 10^{-12}$ Considered not worthy of concern
Non-destructive Excursion	A temperature excursion which may rupture the primary coolant loop and release fission products to the environment but - leaves the reactor shield essentially intact
Normal Operations	Planned and anticipated mission activities and events
Over Moderation	Immersion of reactor in an hydrogenous medium (moderator) resulting in increased neutron reflection into the core causing a reactor excursion
Permanent Shutdown	Enacting provisions which preclude reactor criticality under all foreseeable circumstances
Poison	A material that absorbs neutrons and reduces the reactivity of a reactor
Power Module	The complete reactor/shield, radiator, power conversion system and disposal system unit as provided on the Space Base
Premature Reentry	Any reentry of the reactor from Earth orbit with orbital lifetimes less than the planned (1167 year) orbital decay time of the 990 km disposal altitude
Pre-poison	A poison which is added to the reactor fuel for purposes of controlling reactcity Sometimes referred to as "burnable poison"
Prompt Radiation	The neutron and gamma radiation released coincident with the fission process as opposed to the radiation from fission product decay. Commonly associated with an excursion event
Quasi-Steady State	A term used to describe the condition when a reactor periodically goes critical and then subcritical due to water surging in and out of the core
Radiological Consequences	The radiation exposure effect on personnel and the ecology from a radiation release accident or event
Radiological Hazards	Hazards associated with radiation as differentiated from other sources
Radiological Risk	The term used to define the average number of people anticipated to be affected by radiation in a given mission or phase thereof
Random Reentry	The uncontrolled non-directed reentry of a vehicle from orbit
Reactivity	A measure of the departure of a reactor from critical such that positive values correspond to reactors super-critical and negative values to reactors which are sub-critical (Usually expressed in multiples of a dollar)

GLOSSARY OF TERMS (CONT)

Reactor Fails to Survive Reentry	Reactor/shield is completely disassembled by reentry heating, releasing individual fuel elements and structural debris to the atmosphere
Reactor Survives Reentry	Reactor is not disassembled by reentry heating, radiation shield may be damaged
Reactor/Shield	A system containing the reactor, control drums, gallery and surrounding LiH and Tungsten shield
Relative Probability	Probability of the occurrence of a particular event given a defined set of choices
Repair/Replacement	Consists of (a) physically repairing all faulty systems, or (b) complete replacement of the faulty system(s).
Ruptured	Same as "Breached".
Safety	Freedom from chance of injury or loss to personnel, equipment or property
Safety Catastrophic	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will severely degrade system performance, and cause subsequent system loss, death, or multiple injuries to personnel (SPD-1A).
Safety Critical	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will cause equipment damage or personnel injury, or will result in a hazard requiring immediate corrective action for personnel or system survival (SPD-1A).
Safety Marginal	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will degrade system performance but which can be counteracted or controlled without major damage or any injury to personnel (SPD-1A).
Safety Negligible	Condition(s) such that personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will not result in minor system degradation and will not produce system functional damage or personnel injury (SPD-1A)
Scram System	A separate, possibly automatic, mechanism used to rapidly shut down a reactor.
System Safety	The optimum degree of risk management within the constraints of operational effectiveness, time and cost attained through the application of management and engineering principles throughout all phases of a program
Space Base Program	All aspects of the Space Base mission including all prime and support hardware and personnel both on the ground, at sea or in orbit, which are required throughout all mission phases.
Space Debris	Uncontrolled radioactive or non-radioactive man-made objects in space, these objects may present collision and radiation hazards to earth orbital missions.
Space Shuttle	The manned vehicle used for the transportation of cargo to and from earth orbit A separately launched vehicle (booster) on which the Shuttle is placed provides the initial first stage thrust
Source Terms	Characterization of a radiation hazard with regard to (a) location, (b) magnitude, and (c) exposure mode
Tracer	Material in which isotopes of an element may be incorporated to make possible observation of the course of the element through a chemical, biological or physical process.

GENERAL ELECTRIC

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